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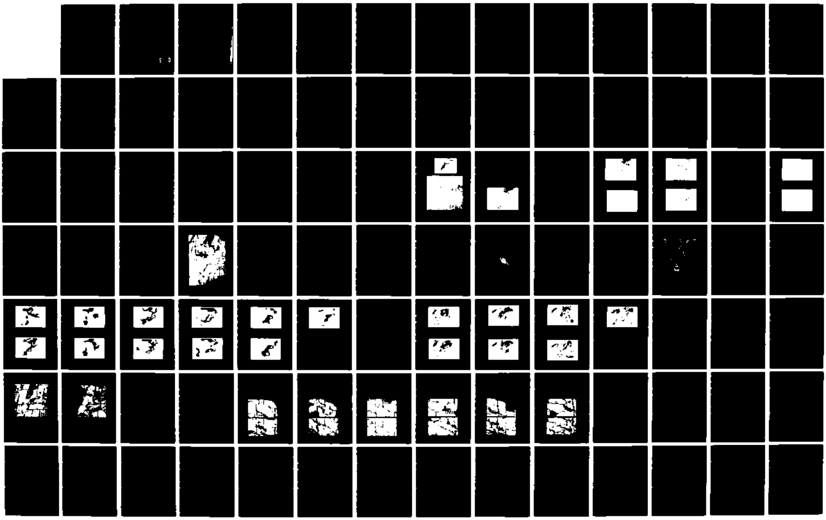

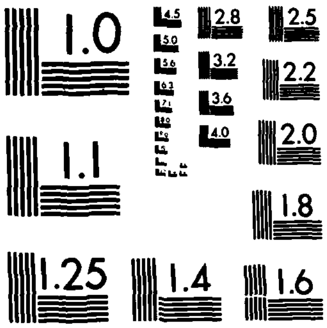

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WEATHER FORECAST ADJUSTMENT USING MODEL OUTPUT CLOUD FIELDS AND DIGITAL SATELLITE DATA

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Final Report
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20 ABSTRACT (Continue on reverse side if necessary and identify by block number)

The technique outlined by Vonder Haar et al., (1977) and Buss (1981), of using digital satellite data to monitor the accuracy of model output derived cloud fields is examined to determine its feasibility and practicability.

Cloud fields are produced from ceiling and cloud amount forecasts based on Model Output Statistic equations, run by the National Weather Service at the Technique Development Lab in Silver Spring, Maryland. ~~There~~ Their cloud fields

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20. Abstract (continued from reverse side)

are displayed on a coordinate system that is compatible with a corresponding display of digitized GOES satellite data. The model output cloud fields are displayed over a 12 hour forecast period to depict what the satellite cloud field should "look like" at some future time. Then as GOES satellite images are received, they are used to verify the model output forecast performance and an assessment is made to accept or alter the forecast.

The technique was found to be both feasible and easily adapted for use on an interactive display system. Simultaneous display of the forecast and observed cloud fields appear to be a useful tool to aid in short range forecasting decisions and for monitoring the existing forecast. Future research should focus on the incorporation of these new shortrange forecast methods into specific Air Weather Service applications.

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FOREWORD

The purpose of this final report is to summarize the work done on AFGL Contract F19628-78-C-0207, 'Use of Quantitative Satellite Data for Objective Mesoscale Weather Forecasting.' This report will also include the final results of the research involving the test and evaluation of the overall short-range forecasting scheme as set forth in the original proposal and subsequent modifications.

This short-range forecasting project was conceived a number of years ago with the realization that numerical models and most other techniques showed an interesting gap in skills during the time periods between 4-12 hours. Prior to 4 hours, persistence and certain statistical methods showed some skill while the LFM style models scored well at the 12 and 24 hour periods. We envisioned an interactive technique that would be developed and tested and targeted directly towards the emerging interactive weather data system that was planned at that time by the air weather service.

The basic approach in our research involved the convergence of several lines of inquiry and study, all of which had a contribution to make to the overall project which we termed FOCAST (FOcused nowCASTing). Appendix A includes portions of the early research proposal and the ideas which we agreed to explore at that time with our colleagues at both at the Air Force Geophysics Laboratory, and the Global Weather Central of the Air Weather Service.

The converging lines of inquiry were as follows:

(1) The development of a 'bridge' between the numerical model

forecast output products presented in quantitative form, e.g. heights, temperaures, winds, etc., and the satellite data also presented in quantitative form (spectral radiances in the visible and infrared and combinations of these two basic parameters). We began a line of inquiry on this project that culminated in the work of Captain Buss and Captain Reinke which is described in the following sections of this report. This portion of the research was quite successful, although several blind alleys were explored and we were rather surprised to learn that the model output parameters of the LFM type were less related to the satellite data than the model output statistics parameters which are a second generation forecast output product.

(2) The second converging line of inquiry which was to culminate in the total FOCAST research was the method of forecast adjustment once an apparent error or nonverification of a 12-hour forecast was detected by the method noted in (1) above. This adjustment had to be quantitative and yet amenable to meteorological operator interaction. During the course of our research we were happy to see that the group at the University of Wisconsin under AFGL contract had also experimented with the extrapolated and interpolated movement of weather such as fronts. We deemphasized this automated bogusing method because several techniques have been developed that can be adapted to the FOCAST scheme. Some results are reported by Reinke (1982).

(3) The third line of inquiry in FOCAST involved the development

and test of more sophisticated automated cloud pattern detection and depiction methods. These are reported in results by Haass and Brubaker, by Smith, et al. (1980), and are the kind also presented by Muench (1980/81). These advanced techniques are to be at the disposal of the forecaster as he works in an interactive mode with the real time data. They would allow him to make decisions regarding the verification or nonverification of forecasts and would aid him in the bogusing or forecast adjustment work as well. We reported, in the papers noted above, success in these items and they were placed in readiness about one year ago for tests when the other parts of the method reached maturity.

All of the intended lines of research inquiry were examined with less emphasis placed on the forecast adjustment method (2 above) than initially expected when the project was initiated in 1978.

As we have indicated in our correspondence during the last year, the research, which is a bold attempt to improve short-range forecasting for Air Force purposes over the very short-range time periods of 4-12 hours, was moving at perhaps 80% of the rate we had anticipated. Thus when the final report was due, we requested a continuation of the work for another year at the same level of effort so we could capitalize on this rather long term research project and bring its benefits fully to the attention of Air Force scientists and forecasters. We understand the decisions that had to be made in mid-1981 between the continuation of this project and other activities. We also understand that the delay in the deployment of the Air Weather Service man interactive Automated Weather Information Dissemination System (AWIDS) also gave rationale for delay of this project. Nevertheless, we believe the results are very encouraging and suggest that a focused team research effort led perhaps by AFGL scientists with the participation of CSU and others would capitalize fully upon these results, and bring together a final product that would be most interesting and useful in the Air Weather Service mission.

ACKNOWLEDGEMENTS

For their assistance in preparing this final report, we thank Dr. Richard H. Johnson, of the Department of Atmospheric Science, Captain Merlyn Forsyth and Captain Norman Buss for their scientific discussions. For assistance in obtaining the MOS data, we thank the Technique Development Laboratory (TDL) in Silver Springs, Maryland, in particular the Air Force Liaisson Officer Capt. Charles French. Professor Thomas Brubaker, Dr. Uwe Haass and several Electrical Engineering students contributed to research related to the present report. Their work is published in separate contract reports.

Our special appreciation is extended to those who spent many hours giving advice and assistance with the CSU satellite ground station and data processing systems, especially Pat Laybe, Tom Cipriani, Bob Green and Deborah Mraz, to Jim Purdom and Dr. Stuart Meunch for their technical comments on the drafts, and to Duayne 'Barney' Barnhart and Jeff Klute for photoprocessing, and to Andrea Adams and Robin Wilson for their expert assistance with the typing and editing of the manuscript.

This research was sponsored by the Air Force Geophysics Laboratory (AFGL), Hanscom Air Force Base, Massachusetts, under Contract No. F19628-78-C-0207.

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1.0 INTRODUCTION

1.1 Statement of Research Objective

The intent of this research is to develop the basic components (software) to assess the feasibility and potential problems of using satellite data to monitor and adjust the forecast movement of cloud fields derived from numerical weather prediction model output. The result of the adjustment would be a more accurate cloud field forecast and, most probably, weather forecast in the 6 to 12 hour forecast time period.

The study will focus on a specific type of cloud forecast that is generated from Model Output Statistics (MOS) (Glahn and Lowry, 1972) but will be aimed at producing a technique that can be used to monitor any cloud forecast that is stratified by cloud height and cloud amount. The research will center around meteorological data and processing capabilities that exist or are scheduled for use at the forecast office level. Specifically the National Weather Service's Automation of Field Operations and Services (AFOS) system and the Air Weather Service's Automated Weather Information Dissemination System (AWIDS) and Satellite Information Dissemination System (SIDS).

1.2 Nature of the Forecast Problem

Weather forecasters in the United States routinely use output from Numerical Weather Prediction (NWP) models to make operational forecasts. In particular those models run at the National Meteorological Center

(NMC) in Suitland, MD, where model output from the Limited Area Fine Mesh (LFM) model is produced every twelve hours (Rieck, 1978) and is made available to the field forecaster approximately two hours after the standard data collection times of 1200 and 0000 GMT. Displays of elements from this forecast model output are transmitted to most weather forecasting stations. Special products derived from this output, such as MOS forecasts, have become an important and routine data source in the forecasters' decision-making process.

These meteorological models are in a constant state of update and improvement, however, and are still not able to predict the state of the atmosphere with complete accuracy (Derouin, 1974, and Houghton, 1976). Thus, they must be adjusted when in error. As a result the forecaster will use observational weather data to assess the performance of the model and adjust the model output when an error is detected or suspected.

Given the limitations of model output and a desire to produce the best possible forecast, one should look for a method of detecting errors in the model output, then develop a technique to correct or adjust those errors. One method that is commonly used is to check the forecast movement of synoptic scale features using information in the Satellite Information Messages (SIMS). SIMS are issued every three hours by regional Satellite Field Service Stations. These messages give a verbal description of synoptic features that are observed on geostationary satellite imagery and will often compare movement of these features, such as fronts or cloudiness associated with vorticity centers, to the movement forecast by the LFM.

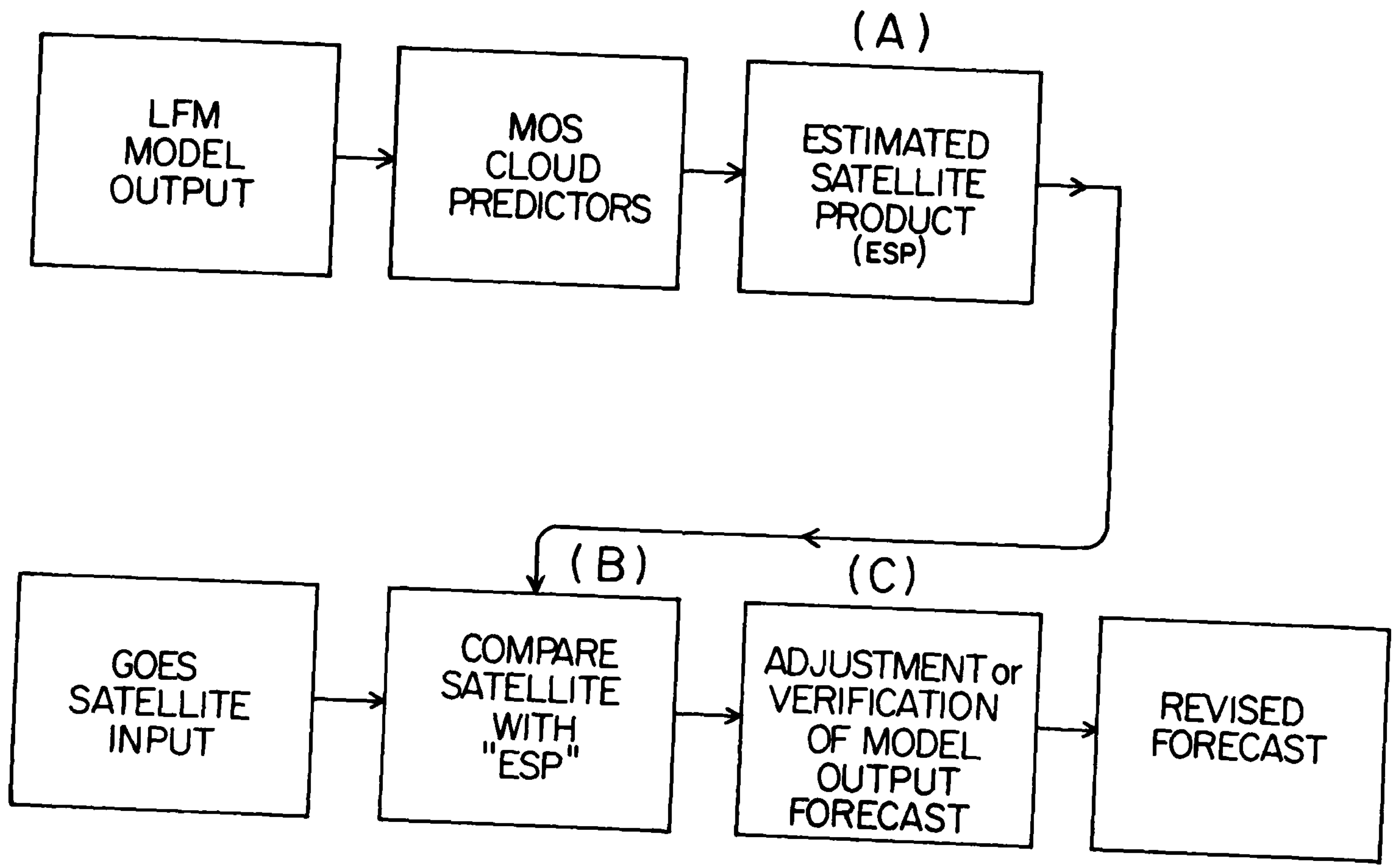

Figure 1. Proposed forecast adjustment method using digital satellite data (Vonder Haar, et al., 1977).

Buss (1981) outlines some of the attempts that have been made to adjust model output forecasts and discusses a technique for using digital satellite data to monitor model performance. This study will expand on that 'FOCAST' (FOcused NowCAST) technique (Vonder Haar, et al., 1977) using the output from Model Output Statistic (MOS) equations to demonstrate how satellite (or in a similar manner, other observational data) can be used to monitor and if necessary adjust the model output forecast.

1.3 Research Plan

The research effort will be focused on (1) assembling enough of the basic components (software) to carry out the proposed forecast adjustment method and (2) testing the feasibility of the method on actual weather conditions having forecast complexity.

The proposed forecast adjustment method is shown in Figure 1. the three specific techniques studied in this paper are (A) the determination and display of the estimated satellite product or ESP, (B) the comparison of digital satellite data with the ESP, and (C) the verification or adjustment of a model output forecast by use of the difference between ESP and the ESP and the satellite data. Two of the items in the diagram, the MOS cloud predictors and the GOES satellite data processing, have been developed by others. The final component, a forecast revised by quantitative means, must await future research.

The term 'ESP' is used to describe a display of what a satellite image should look like at some future time. In effect it is a 'forecast satellite image'. The technique to determine the ESP is covered in more detail in Section 2.3.1.

Figure 2 gives a summary of the technique proposed for comparison or 'bridging' of the ESP and satellite data. Once the two cloud fields have been displayed, the forecaster must determine (A) which cloud fields to compare, and (B) how to monitor the movement of the cloud fields. In selecting which cloud fields to monitor, the selection can be based on a specified area of interest such as an aviation forecast region, or it can be a specific cloud field such as the clouds associated with a vorticity maximum or a frontal cloud band. Independent movement, (C) in Figure 2, refers to monitoring the growth, decay, or movement of the ESP cloud field and comparing it to a separately measured satellite cloud field movement. For example the forecast movement of the center of an ESP cloud field can be plotted over a 6 hour period and then the movement of a corresponding actual cloud field measured from the satellite can be plotted and compared to the predicted ESP movement. A statistical bridge (D) refers to some method of developing a direct relationship between the two cloud fields. An example would be to assign a numerical value to each grid point of a cloud field according to its height or aerial coverage, then develop a statistical relationship between the ESP and satellite cloud fields at each point in the data array. This type of bridge would be advantageous for computer processing an extremely large data set, or when subjective analysis is not convenient.

Figure 3 completes the description of the research plan by showing a proposed method for using the compared fields to verify or adjust the model output forecast. If such a comparison shows a discrepency in the forecast cloud field, the forecaster must decide whether the conflict is due to a simple displacement, or if the observed cloud field is showing

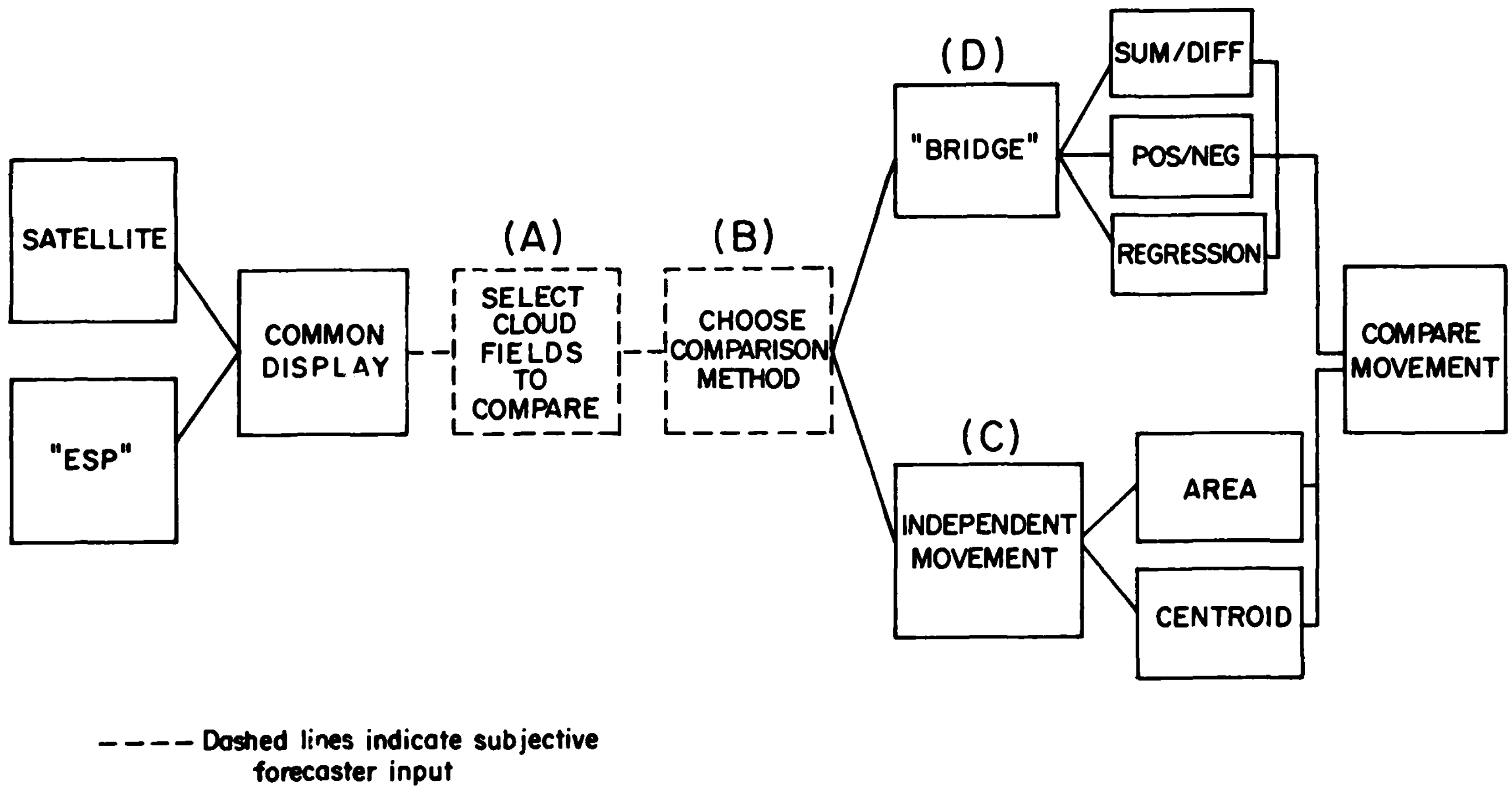

Figure 2. Method for comparison, or 'bridging' of satellite data and 'ESP'.

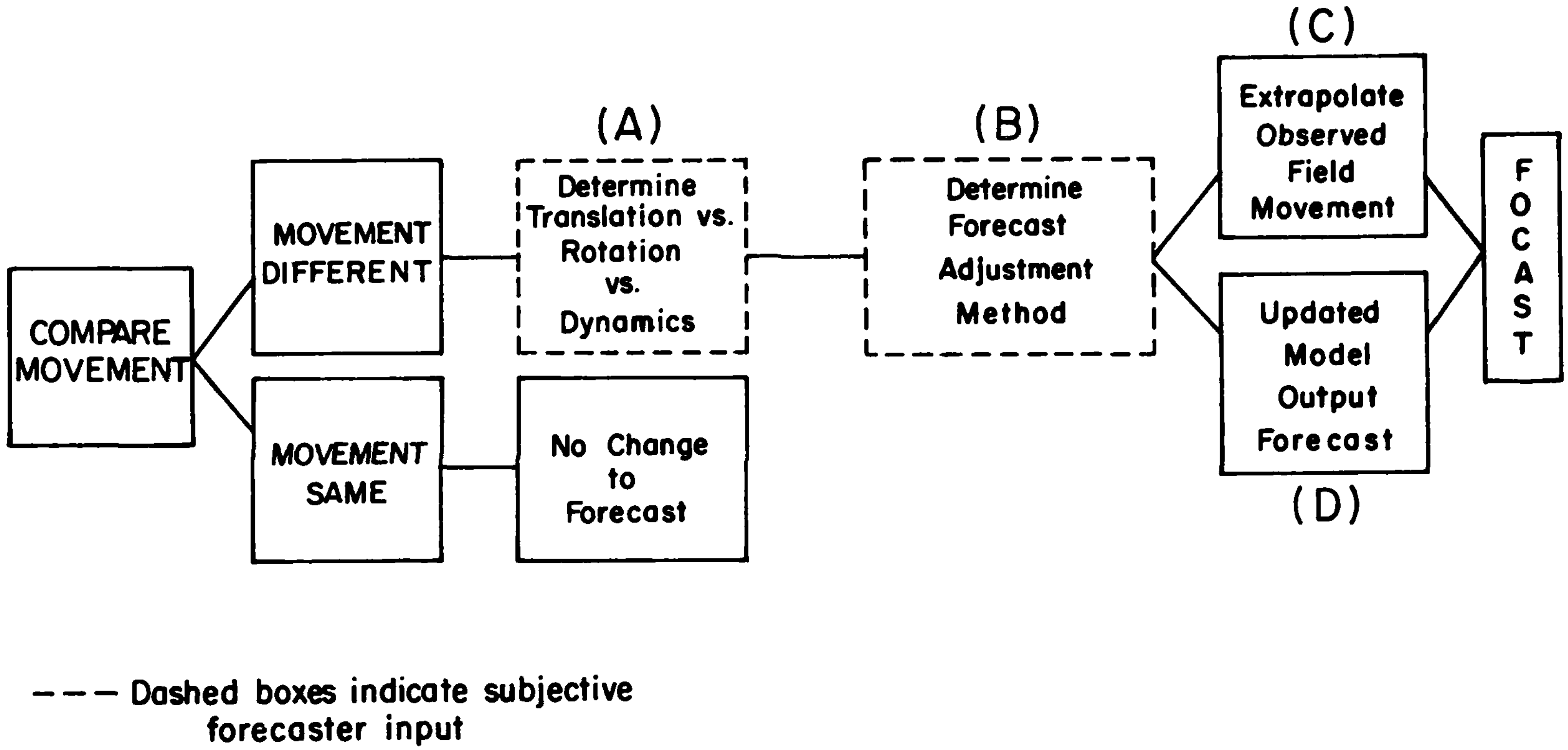

Figure 3. Proposed method for using the compared displays to adjust the forecast movement of the MOS cloud field when it is in error.

dynamic growth or rotation that was not forecast by the model (A). Based on the assessment the forecaster must then decide on an adjustment technique (B). The forecast adjustment can be an extrapolation of observed cloud field movement (C) or a new forecast based on an updated set of model output statistics or a persistence probability type of forecast (D).

Once these techniques have been demonstrated independently in the present paper a case study will be used to follow the performance of a MOS cloud forecast over a two day period in November 1979, to test the feasibility and practicability of the overall forecast adjustment method.

2.0 DATA AND DATA PROCESSING

To use satellite data to monitor the accuracy of a given numerical weather prediction model forecast, one must first construct a cloud field forecast that most closely represents the model output elements. One difficulty that has plagued meteorologists, in particular general circulation modelers, is the accurate forecast of the presence of a cloud (Starr and Cox, 1977). For example, the LFM model does not directly produce a cloud field forecast, but produces a forecast of the following elements: U and V wind components (layer mean wind on a constant pressure or height surface), temperature, thickness between pressure surfaces, and precipitable water content. From these elements others are derived such as vertical velocity, vorticity, and divergence. From this combined set of elements then, a forecast is made for weather elements such as clouds and precipitation. One widely accepted technique is the use of model output statistics set forth by Glahn and Lowry.

2.1 Model Output Statistics (MOS)

The method of producing MOS is, in brief, to gather a data sample of sufficient size that contains the element you wish to model or predict and the elements you will use as predictors. A statistical relationship is then developed using a multiple linear regression screening procedure (see also Buss, 1981). The result is a prediction equation that gives a probability that a cloud (or other weather element) will exist given the value of certain model output elements. Pertinent to this study is the MOS cloud forecast (Vercelli, 1978) which predicts cloud amount and ceiling height using model output elements as predictors.

The MOS equations use the following output elements from the LFM model: relative humidity, precipitable water, amount of precipitation, wind components, vertical velocity, constant pressure height, and temperatures. The prediction equations use not only model output but long term climatology for each region and station. MOS prediction equations are stratified by region (Figure 4) based on data gathered at 233 conterminous U.S. stations (Table 1). Separate equations run for the cool season (October through March) and the warm season (April through September). The data used in the regression cover a 12 year period and includes certain elements that are unqiue to each station or the time of year such as: station elevation, sine and cosine of the date and latitude and the initial surface observation at the station (this initial observation can be three hours past the LFM data base time).

MOS prediction equations produce a probability forecast for each cloud height and cloud amount category. To determine the 'best' category the percentages are weighted and the category with the highest weighted percentage is the one that is for%cast (Figure 5). Weighting is based primarily on the frequency of occurrence of a given cloud category in the climatological data set.

Model output statistics are compiled twice daily using model output from the Limited Area Fine Mesh (LFM) model run at the National Meteorological Center in Suitland, MD. Categorical forecasts of cloud

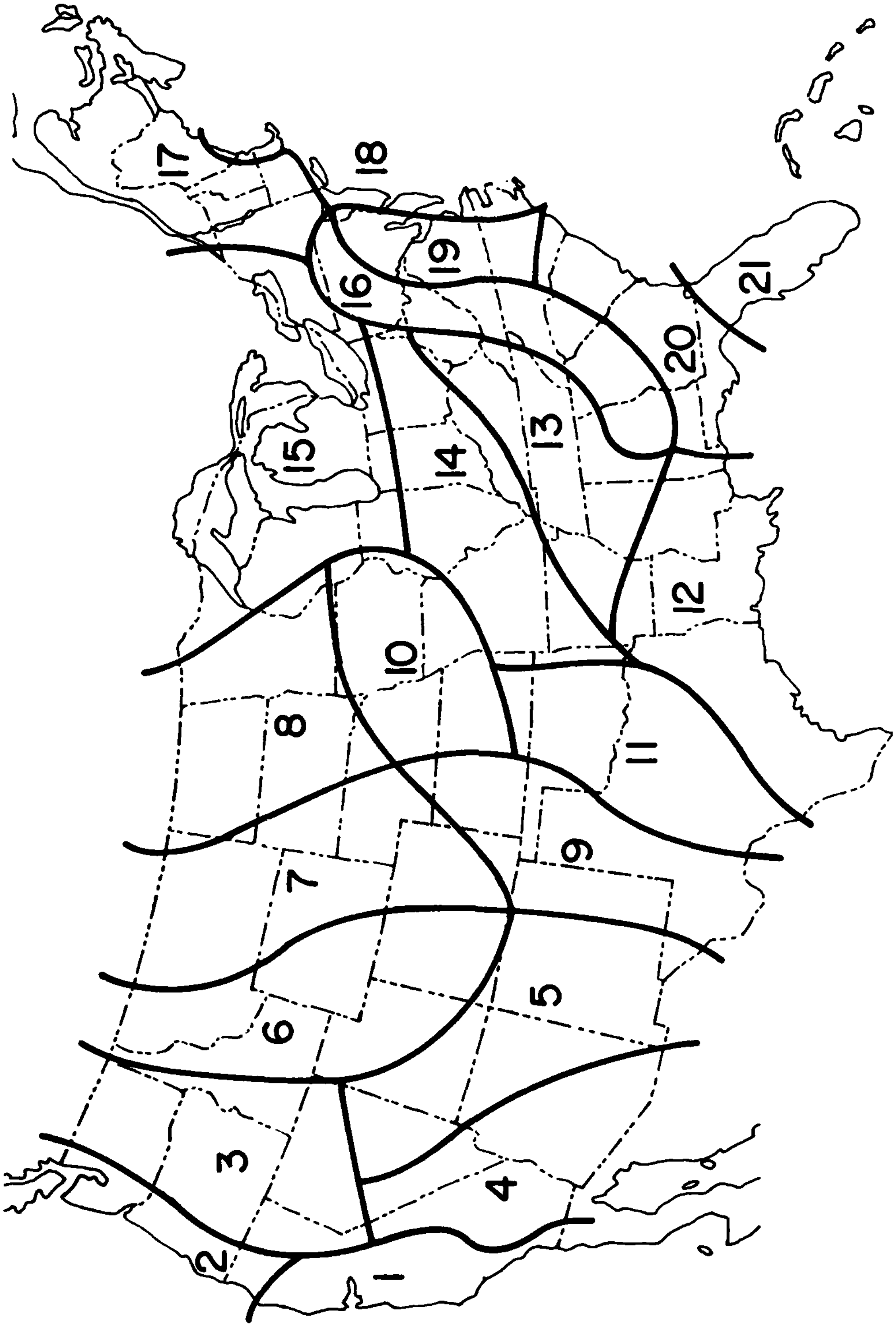

Figure 4. MOS 'cool season' forecast regions (Carter, 1976).

Table 1

Stations used in the development of model output statistics (MOS).

Name	Station	Name	Station
FLG	Flagstaff, AZ	AVL	Asheville, NC
MCN	Macon, GA	AGS	Augusta, GA
SAV	Savannah, GA	HSV	Huntsville, AL
HTS	Huntington, WV	GSP	Greenville, SC
BKW	Beckley, WV	DFW	Dallas-Ft Worth, TX
ICT	Wichita, KS	LCH	Lake Charles, LA
JAN	Jackson, MS	COU	Columbia, MO
MCI	Kansas City, MO	BGM	Binghamton, NY
BFD	Bradford, PA	DAB	Daytona Beach, FL
FMY	Fort Myers, FL	EYW	Key West, FL
MIA	Miami, FL	ORL	Orlando, FL
TPA	Tampa, FL	PBI	West Palm Beach, FL
BVE	Boothville, LA	VCT	Victoria, TX
MSY	New Orleans, LA	BRO	Brownsville, TX
SAT	San Antonio, TX	CRP	Corpus Christi, TX
IAH	Houston, TX	RDU	Raleigh-Durham, NC
GSO	Greensboro, NC	EKN	Elkins, WV
LYH	Lynchburg, VA	ORF	Norfolk, VA
PHL	Philadelphia, PA	RIC	Richmond, VA
ROA	Roanoke, VA	DCA	Washington, DC
ILM	Wilmington, NC	ILG	Wilmington, DE
MEI	Meridian, MS	CRW	Charleston, WV
AHN	Athens, GA	ATL	Atlanta, GA
BHM	Birmingham, AL	TRI	Briston, TN
CHS	Charleston, SC	CLT	Charlotte, NC
CHA	Chattanooga, TN	PNS	Pensacola, FL
CAE	Columbia, SC	JAX	Jacksonville, FL
TYS	Knoxville, TN	MEM	Memphis, TN
MOB	Mobile, AL	MGM	Montgomery, AL
BNA	Nashville, TN	ESF	Alexandria, LA
SHV	Shreveport, LA	AUS	Austin, TX
ACT	Waco, TX	DAL	Dallas, TX
ABI	Abilene, TX	LIT	Little Rock, AR
FSM	Fort Smith, AR	SPS	Wichita Falls, TX
OKC	Oklahoma City, OK	TUL	Tulsa, OK
BTR	Baton Rouge, LA	CNK	Concordia, KS
DDC	Dodge City, KS	STJ	St Joseph, MO
STL	St Louis, MO	SGF	Springfield, MO
TOP	Topeka, KS	BGR	Bangor, ME
CAR	Caribou, ME	LGA	New York, NY
BUF	Buffalo, NY	EWR	Newark, NJ
ALB	Albany, NY	ABE	Allentown, PA
BOS	Boston, MA	BDL	Hartford, CT
BTV	Burlington, VT	CON	Concord, NH
HAR	Harrisburg, PA	PWM	Portland, ME
PVD	Providence, RI	ROC	Rochester, NY
SYR	Syracuse, NY	AVP	Scranton, PA

Name	Station	Name	Station
IPT	Williamsport, PA	MDW	Chicago Midway, IL
CLE	Cleveland, OH	CMH	Columbus, OH
FNT	Flint, MI	FWA	Fort Wayne, IN
LAN	Lansing, MI	MSN	Madison, WI
MKE	Milwaukee, WI	MKG	Muskegon, MI
PIA	Peoria, IL	SSM	Sault St. Marie, MI
SBN	South Bend, IN	TVC	Traverse City, MI
YNG	Youngstown, OH	ERI	Erie, PA
CAK	Akron-Conton, OH	GRB	Green Bay, WI
DLH	Duluth, MN	FAR	Fargo, ND
INL	Intl. Falls, MN	LSE	Lacrosse, WI
LSE	Lacrosse, WI	MSP	Minneapolis, MN
MLI	Moline, IL	RST	Rochester, MN
ABR	Aberdeen, SD	BRL	Burlington, IA
DSM	Des Moines, IA	GRI	Grand Island, NB
HON	Huron, SD	MCW	Mason City, IA
OMA	Omaha, NB	SUX	Sioux City, IA
FSD	Sioux Falls, SD	EAU	Eau Claire, WI
DRT	Del Rio, TX	MAF	Midland, TX
SJT	San Angelo, TX	AMA	Amarillo, TX
TCC	Tucumcari, NM	ABQ	Albuquerque, NM
DEN	Denver, CO	GLD	Goodland, KS
GJT	Grand Junction, CO	FMN	Farmington, NM
LGB	Long Beach, CA	TPH	Tonopah, NV
ELY	Ely, NV	BFL	Bakersfield, CA
BCE	Bryce Canyon, UT	TUS	Tucson, AZ
DAG	Daggett, CA	LAS	Las Vegas, CA
LAX	Los Angeles, CA	PHX	Phoenix, AZ
RNO	Reno, NV	SAN	San Diego, CA
INW	Winslow, AZ	YUM	Yuma, AZ
OAK	Oakland, CA	SAC	Sacramento, CA
SFO	San Francisco, CA	SCK	Stockton, CA
SMX	Sante Maria, CA	BIS	Bismarck, ND
MOT	Minot, ND	CYS	Cheyenne, WY
LND	Lander, WY	LBF	North Platte, NB
PIR	Pierre, SD	RKS	Rock Springs, WY
BFF	Scottsbluff, NB	SHR	Sheridan, WY
BIL	Billings, MT	CPR	Casper, WY
RAP	Rapid City, SD	EKO	Elko, NV
SLC	Salt Lake City, UT	WMC	Winnemucca, NV
BOI	Boise, ID	BNO	Burns, Oregon
GTF	Great Falls, MT	HLN	Helena, MT
FCA	Kalispell, MT	MSO	Missoula, MT
PDT	Pendleton, OR	PIH	Pocatello, ID
GEG	Spokane, WA	LDL	Lovelock, NV
RBL	Red Bluff, CA	EUG	Eugene, OR
MFR	Medford, OR	OLM	Olympia, WA

Name	Station	Name	Station
PDX	Portland, OR	RDM	Redmond, OR
SLE	Salem, OR	SEA	Seattle-Tacoma, WA
YKM	Yakima, WA	ACV	Arcata, CA
OTH	North Bend, OR	COS	Colorado Springs, CO
TCS	Truth or Consequences, NM	PUB	Pueblo, CO
CDC	Cedar City, UT	FAT	Fresno, CA
BWI	Baltimore, MD	HAT	Cape Hatteras, NC
ACY	Atlantic City, NJ	IAD	Washington-Dulles, VA
WAL	Wallops Island, VA	TLH	Tallahassee, FL
CVG	Cincinnati, OH	DAY	Dayton, OH
EVV	Evansville, IN	IND	Indianapolis, IN
LEX	Lexington, KY	SDF	Louisville, KY
SPI	Springfield, IL	LFK	Lufkin, TX
RSL	Russell, KS	GGW	Glasgow, MT
HVR	Havre, MT	ISN	Williston, ND
AST	Astoria, OR	UIL	Quillayute, WA
BDR	Bridgeport, CT	MSS	Massena, NY
JFK	New York, NY	HIL	Houghton Lake, MI
RFD	Rockford, IL	PIT	Pittsburgh, PA
TOL	Toledo, OH	ORD	Chicago, IL
DTW	Detroit, MI	APN	Alpena, MI
GRR	Grand Rapids, MI	DBQ	Dubuque, IA

FOUS12 KWBC 201720
HDNG FOUS12 MOS FCSTS LFM GUIDANCE 2/20/81 1200 GMT

DATE/GMT	20/18	21/00	21/06	21/12	21/18	22/00	22/06	22/12
DFW POP06		5	2	5	10	20	10	20
POP12				5		20		20
QPF06		000/1	000/1	000/1	000/1	000/1		
QPF12				0000/1		000X/1		100X/1
TSTM				9		12		8
* POPT		0000/3	0000/3	0000/3	0000/3	0000/3	0001/3	0007/3
* POSH				99 99/0				
MN/MX				53		73		44
TEMP	74 83	76 66	63 61	59 61	67 69	65 57	53 50	48 49
DEWPT	54 53	53 55	56 56	55 56	56 54	53 52	49 46	43 43
WIND	1910	1813	1814	1812	2315	3210	3314	3317
CLDS	6410/2	5320/2	6212/2	3115/4	2224/4	4222/2	8101/1	9100/1
CIG	000009	000003	000119	001215	001325	000117	000119	000019
VIS	000029	000009	000009	000018	009019	000009	000009	000009
C/V	6/6	6/6	6/6	5/6	5/6	6/6	6/6	6/6
OBVIS	8101/1	8101/1	8002/1	7002/1	6103/4	7102/3	8002/1	8001/1

CLDS - CIG - VIS: CLOUD AMT, CEILING HGT AND VISIBILITY TPB 234
FORECASTS (TENS OF PERCENT) OF PROBABILITY OF OCCURRENCE OF EACH OF SEVERAL CATEGORIES FOR EACH ELEMENT. CATEGORIES ARE AS FOLLOWS:

FCST	CLOUDS*	CEILING(FT)	VISIBILITY(MI)	*CLOUD AMT
1	0-1 CLR	<200	< 1/2	IS OPAQUE
2	2-5 SCT	200-400	1/2 - 7/8	SKY COVER
3	6-9 BKN	500-900	1 - 2 1/2	IN TENTHS;
4	10 OVC	1000-2900	3 - 4	VALUE AFTER
5		3000-7500	5 - 6	/ IS BEST
6		>7500	>6	CATEGORY.

C/V: CEILING AND VISIBILITY TPB 234
BEST CATEGORY OF CEILING AND VISIBILITY DERIVED FROM SIX CATEGORY FORECAST DESCRIBED ABOVE.

Figure 5. Sample of FOVS 12 bulletin transmitted to weather forecast offices to give probability and categorical forecasts of various forecast elements.

amount and ceiling height are then distributed to National Weather Service forecasters via facsimile and/or teletype networks. A similar product is produced by the Air Weather Service at the Global Weather Central, Offutt AFB, Nebraska. Figure 6 is an example of the FOUS 12 bulletin that contains a MOS Cloud forecast. The MOS forecasts are valid at run time plus 3, 6, 12, and every 6 hours through 48; however, only the forecasts valid at 6, and every 6 hours are transmitted to field weather stations. The NWS MOS forecast is available at approximately 4 hours past the rawinsonde data collection time. (The AFGWC product is currently available at 7 hours after data collection.)

A key point is that the MOS cloud forecast is a result of both the observational (climatological) and the dynamic predictors used in the regression screening process. For short time periods (1-6 hours) the MOS equations tend to favor surface observations and climatology in the screening regression, while longer forecast time periods favor the dynamic model output (Vercelli).

2.2 Satellite Data

Satellite data used in this study were collected by the Colorado State University Department of Atmospheric Science Direct Readout Satellite Ground Station (DRSGS). Data were taken from the GOES-East satellite, which is in a geosynchronous orbit with a satellite subpoint near 75 degrees west on the equator. Hourly infrared (IR) and visual data were collected, however, only the IR data were used in the present study to allow for stratification of cloud masses by height (temperature) and to allow the same technique to be applied during daytime and nighttime forecast periods.

The GOES-East satellite begins scanning the full earth disc on the hour and half hour. Scans of the U.S. are taken from north to south between 3 minutes and 8 minutes past the hour (most synoptic observations are taken between 15 and 5 minutes prior to the hour). The satellite imagery processed at Colorado State University can be navigated and displayed by computer within 10 minutes past the hour.

The portion of the image used in our study was the central third of the U.S. This area was chosen to minimize the effects of mountainous terrain on the interpretation of IR satellite imagery. The digital satellite data were collected at a resolution of approximately 0.1 degree latitude per picture element (pixel). This corresponds to a

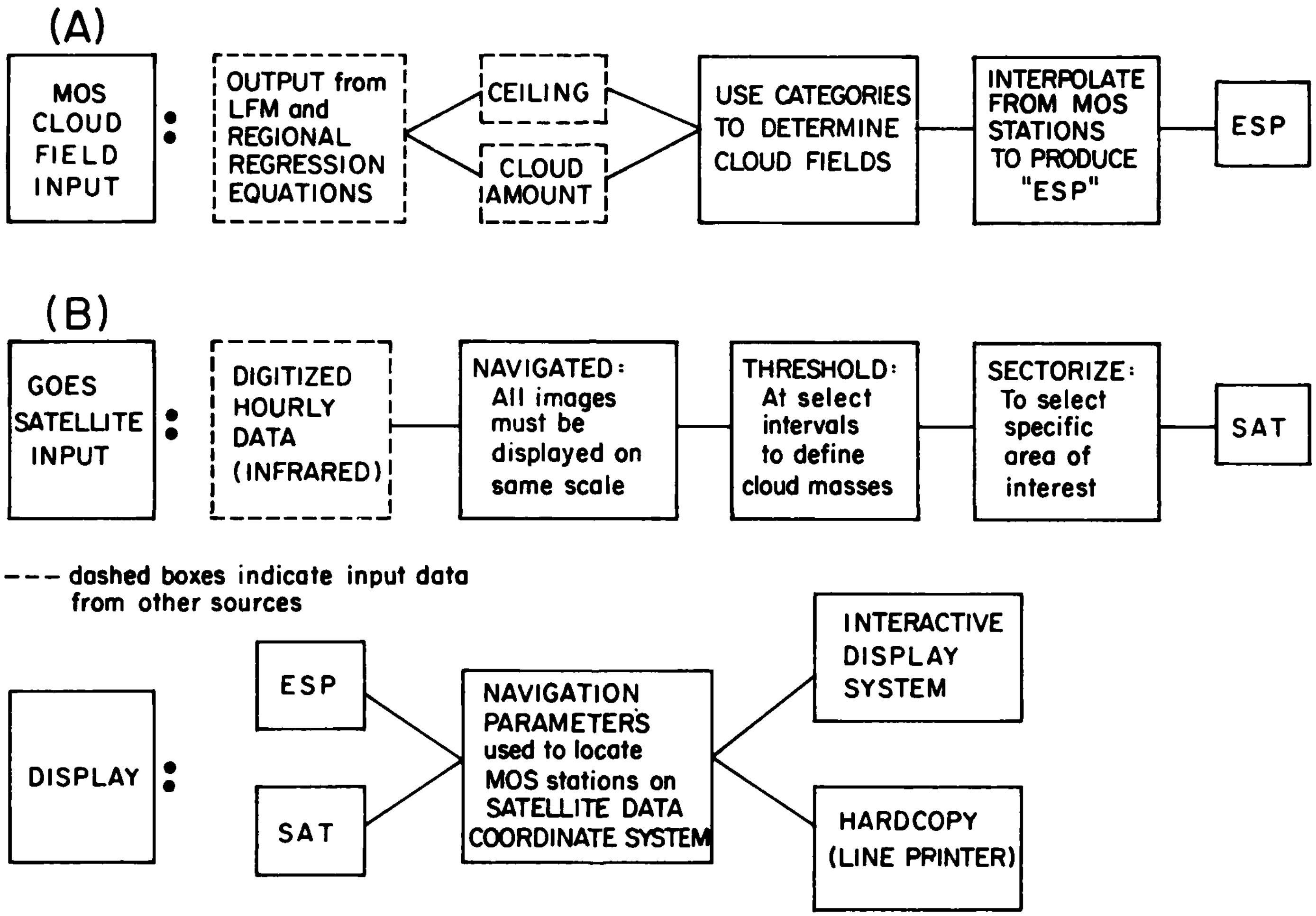

Figure 6. Method for display of model output (MOS) data and satellite imagery.

resolution of approximately 10 km x 10 km at the center of the data display.

The digital data were navigated to convert line and element of the digital data to latitude and longitude using a routine developed by Smith and Phillips (1972). An outline of the U.S. was then added to the data using a plotting routine developed at CSU, and successive hourly images were aligned with each other to insure a proper navigation. This is done by 'looping' the images and noting whether a geograhic feature remains in the same place on the display screen.

One point that should be noted here is high level clouds (greater than 7500 feet) will be displayed at a somewhat greater distance from the satellite subpoint than they actually occur due to a parallax error. In addition, distant clouds will appear radiatively cooler and thus presumed to be higher due to atmospheric attenuation as the optical path length increases.

A method for determining cloud displacement corrections is given by Weiss (1978). For the data used in this study the correction for a cloud at an altitude of 15 km located at 45°N and 105°W would be on the order of 40 km while a 15 km high cloud would be displaced approximately 10km away from the satellite at 30°N and 90°W. These two points represent the extremes of the data display. This displacement then is on the order of 1 to 4 pixels depending on the location and the height of the cloud.

The correction due to atmospheric attenuation will vary according to the latitude and time of year. This is due to the variability of the primary IR attenuator which is water vapor. Using a radiative transfer equation developed at CSU, a comparison was made between the lower atmosphere temperature measured by rawinsonde balloons and the temperature calculated from the satellite radiance at the balloon release sites under a clear sky condition but taking water vapor attenuation into account. The correction due to atmospheric attenuation on the dates used in this study was found to average less than 1°C (Reinke, Magnusdottir, and Conley, 1981). This correction in turn corresponds to a height correction of several hundred meters and will not be considered in this study.

2.3 Description of Displays and Analysis Techniques

To display the MOS and satellite cloud fields with the same geographic location, a program was developed for this study to assign each MOS station a location in the satellite data array. The latitude and longitude of the MOS stations was converted to an array line and element using the satellite navigation information. Figure 6 gives a flow diagram that summarizes how the ESP and satellite data were processed to produce the data displays used in this study. The display procedure will be described in the following paragraphs.

Two types of display were developed, one was to display the satellite imagery and ESP on an interactive system (COMTAL) and the other on a line printer (Figure 7). The advantages to using the COMTAL are that data can be manipulated quickly, and a color display aids data analysis, specifically:

1. The ESP and satellite images can be stored on tape or disk and recalled to the screen with a display time of approximately 12 seconds per image, or stored on memory planes with instant recall (1/30th of a second).

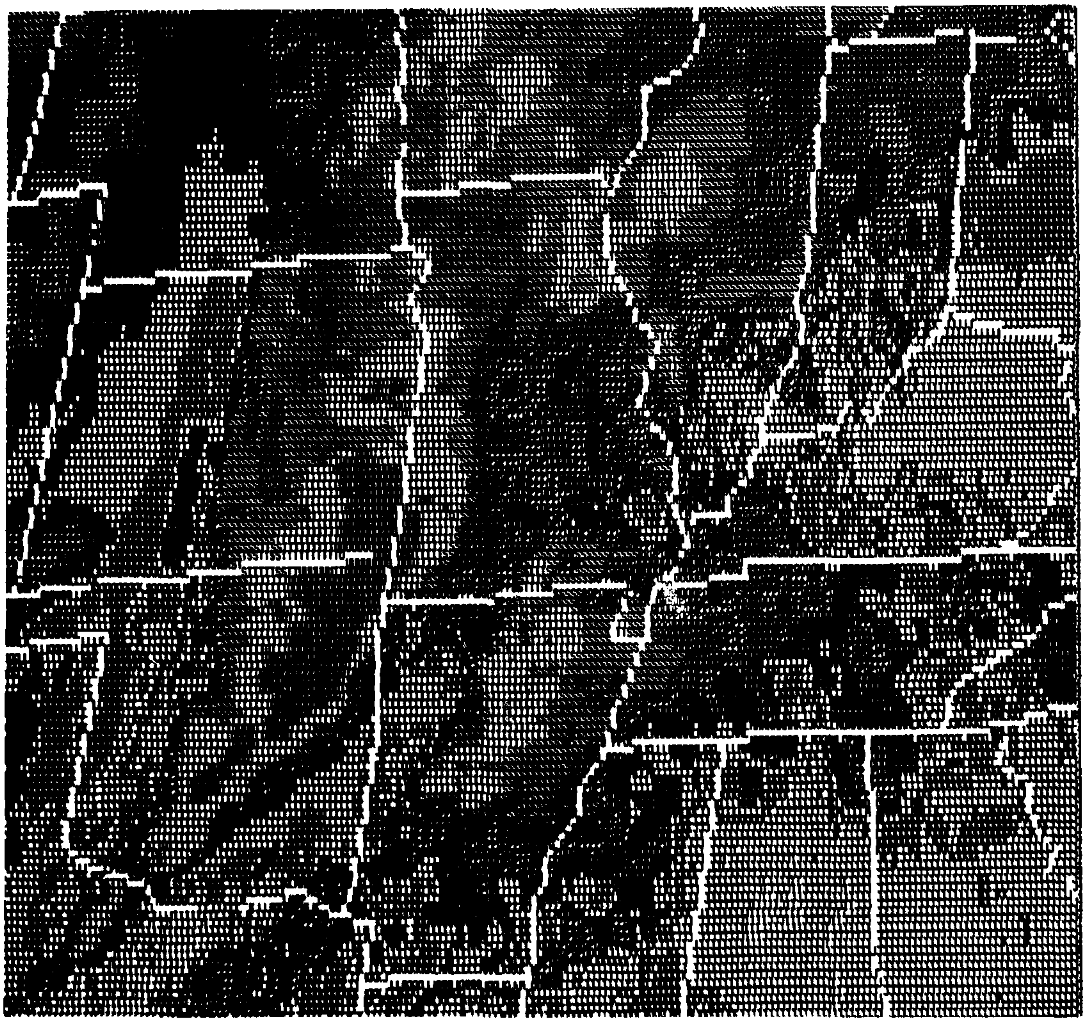

Figure 7. An example of satellite data displayed on the COMTAL (top) and on a lineprinter (bottom). Both displays are 21/0000Z Nov 79 data.

2. The images can be displayed in animation (looping) to show cloud field motion.

3. The images can be 'zoomed' to show specific areas of interest (Figure 8).

4. Color can be added to 'contour' like cloud fields (Figure 9).

5. Cloud masses can be isolated and transferred to a separate graphics storage plane to watch movement of a specific cloud field (Figures 10-14).

The advantage of having a line printer copy (hardcopy) is that the forecaster can, in the absence of an interactive display, perform a 'hand analysis' of cloud field motion using the same techniques described above with the exception of looping. By displaying the MOS cloud field and satellite image on the same scale, a forecaster could also use a clear acetate overlay to trace cloud mass movement and manually compute forecast adjustments.

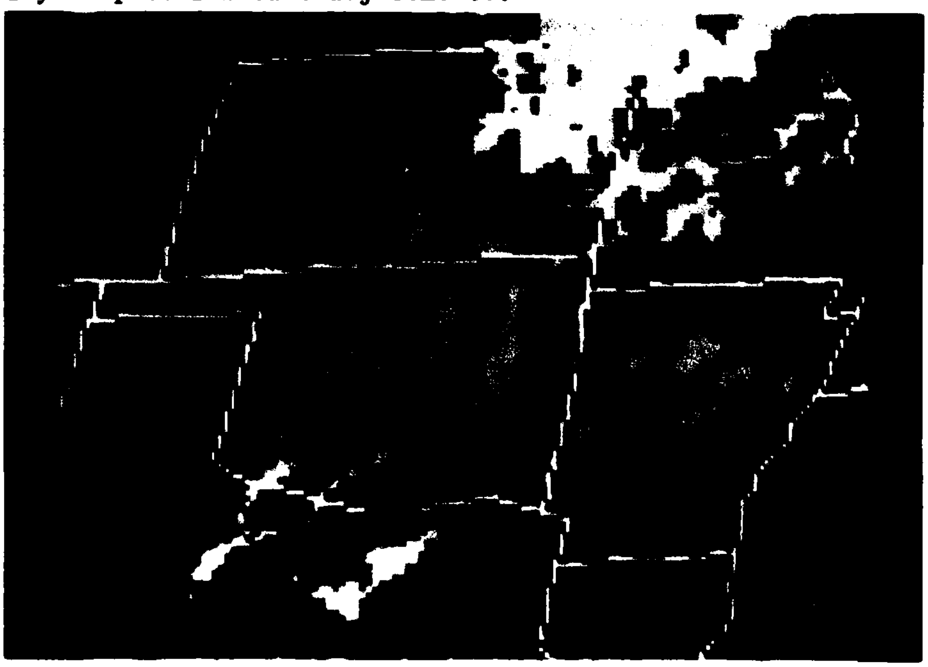

Figure 8. 'Zoomed' image showing cloud band over Oklahoma (20/2100Z).

2.3.1 Estimated Satellite Product (ESP)

ESP is a term used by Vonder Haar, et al. (1980) and Buss (1981) to describe a display that represents a forecast of what a satellite cloud field should 'look like' at a specified time. In essence it is a generic term that will be applied in this study to the MOS cloud field forecast. It could also be applied to any forecast cloud field since that forecast should represent what a satellite will 'see' if it is displayed as a height stratified cloud field.

To create the ESP, (Figure 6 [A]) MOS data were acquired from the Techniques Development Lab (TDL) in Silver Springs, MD. The data were reformatted from the TDL format to be processed on the VAX 11/780 at the CSU Department of Atmospheric Science. Algorithms were then developed to remove ceiling and cloud category information for each of the 233 MOS stations and group them by date and data base (00Z or 12Z). The ceiling and cloud categories were then combined to produce a set of categories from '0' to '9'. In this form the cloud category would be assigned to the array location as a single numeric character. Table 2 gives a list of the MOS ceiling and cloud cover categories and Table 3 shows how they were combined to assign a single cloud field category. Also listed in Table 3 are the colors used when the ESP is displayed on the COMTAL.

To fill in the data array between MOS stations, a routine was written to interpolate out to each array location. The interpolation scheme is based on an analysis technique proposed by Cressman (1959). At each point in the array the program searches through the 233 MOS stations until it locates the five closest. It then assigns weights to the cloud category value at each station by the following:

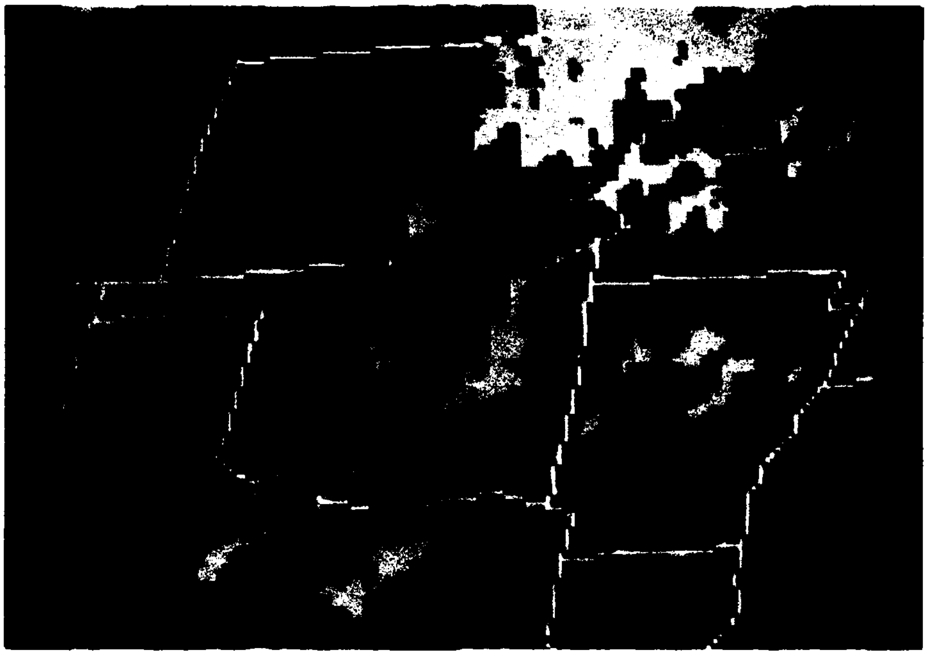

Figure 9. Example of a 'contouring' technique using a red colored graphic to outline the clouds in the 'green' categories in Figure 8.

Figure 10. Isolated display of a cloud field on a graphic plane.

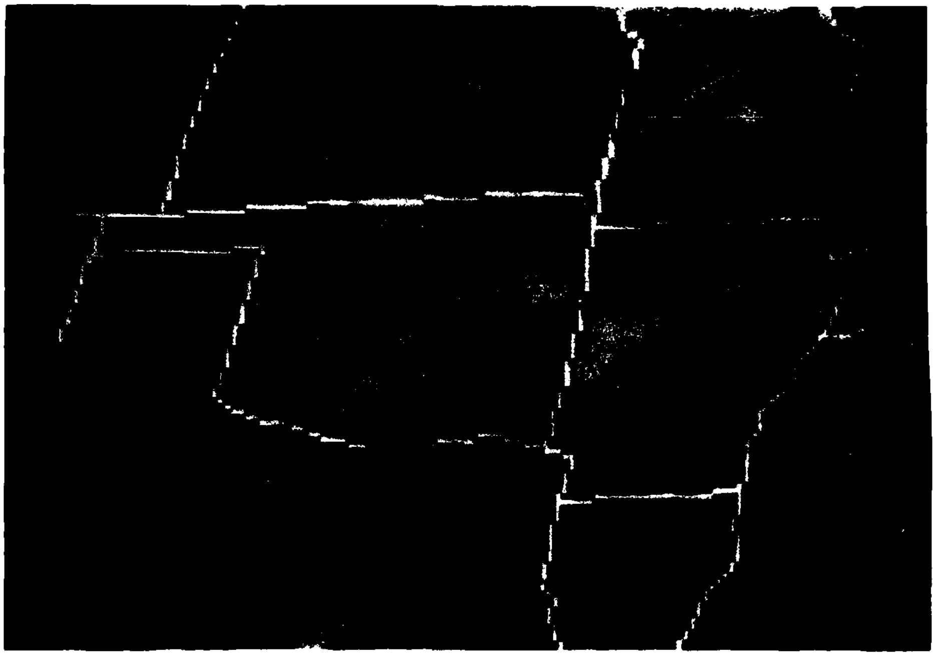

Figure 11. 20/2200Z zoomed image.

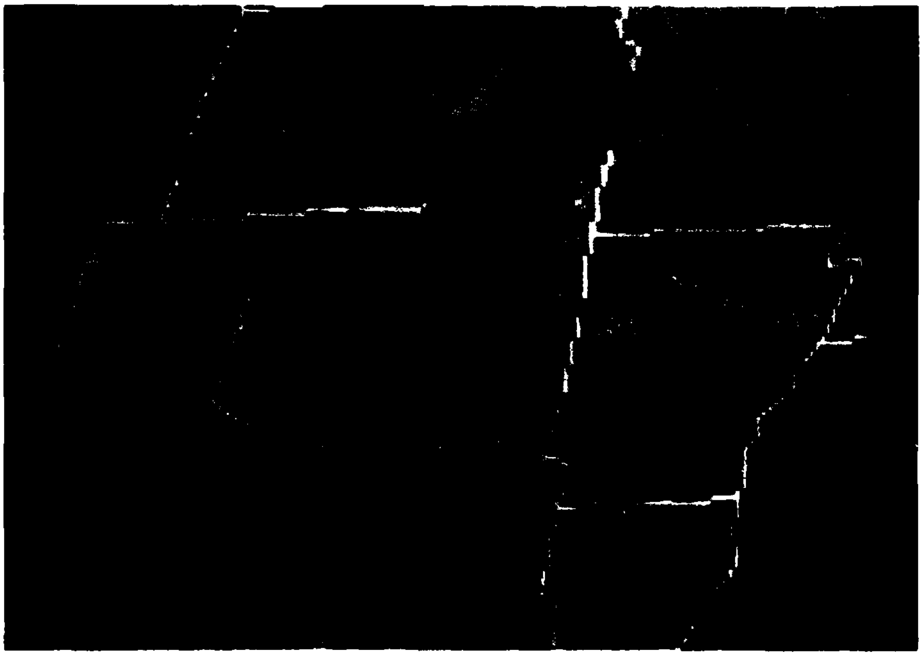

Figure 12. Green colored graphic over the highest cloud categories (Figure 11).

Table 2

MOS ceiling and cloud amount categories.

Category	Ceiling (feet)	Sky Cover (tenths)
1	< 200	0 - 1
2	200 - 400	2 - 5
3	500 - 900	6 - 9
4	1000 - 2900	
5	3000 - 7500	
6	> 7500	10

Table 3

Combined cloud categories and colors assigned to each category for interactive display.

ESP Number	ESP Color	Cloud Category
9	Lt Green	> 7500
8	Dk Green	> 7500
7	Yellow	3000 - 7500
6	Mustard	3000 - 7500
5	Lt Brown	1000 - 2900
4	Dk Brown	1000 - 2900
3	Lt Maroon	500 - 900
2	Dk Maroon	500 - 900
1	Lt Blue	200 - 400
0	Dk Blue	SCT - Clear

SCT = 2-5 Tenths   BKN = 6-9 Tenths   OVC = 10 Tenths

Figure 13. Isolated graphic of the 21/2200Z cloud field.

Figure 14. Display of the 20/2100Z and 20/2200Z cloud fields.

$$W_p = (D^2 - D_p^2)/(D^2 + D_p^2)/W$$

where: W_p = the weight at point P

D = the distance to the farthest point (point 5)

D_p = the distance to point P

W = the sum of $(D^2 - D_p^2)/(D^2 + D_p^2)$ at the four closest points

The value at the array location is then given by:

$$Val = W_{P1}\ Val_{P1} + W_{P2}\ Val_{P2} + W_{P3}\ Val_{P3} + W_{P4}\ Val_{P4}$$

where: Val_{Pn} = the value of the cloud category at one of the four closest points.

Because of the sparsity of data points (Figure 15) the cloud field patterns may not be an accurate display of the forecast cloud field, however, for the purpose of this study, the cloud fields do 'appear' as one would expect a cloud field to look (Figure 16). To check the interpolation scheme two ESP cloud fields were hand analyzed by separate individuals. The resultant fields matched the computer-produced ESPs with regard to the location of maxima, minima and gradients. The 'spiked' appearance on several of the ESPs is a result of the interpolation routine, and the sparsity of data points. In regions where data are more plentiful, the routine produces a smoother pattern.

It should also be noted here that the cloud fields displayed on the ESP may not be an exact representation of the ceiling forecast for a given location on the map. For example a category '5' ceiling (1000-2900 foot overcast) is not always found geograhically between category '3' (500-900 foot overcast) and category '7' (3000-7500 foot overcast) ceilings. The interpolation scheme does, however, show the 'centers of action' in the cloud field forecast and should give a representative display of the movement of cloud fields during the period of the forecast.

2.3.2 Observed Cloud Field (OBS)

The display of verifying observations was constructed in the same fashion as the ESP, using the MOS cloud height and amount categories. Only those surface airways observations taken at MOS stations were used in the OBS display to allow for a compatible data set when comparing an ESP to an OBS.

2.3.3 Satellite Data

Satellite data were stratified into 26 equal temperature intervals to correspond to the 26 alphabetic characters for display on the line printer. Each character represents a 'brightness count' interval of 10. This is done for convenience as the IR satellite data is composed of an array of values that range from 0 to 256. These brightness counts correspond to the amount of radiation detected at each sampling point in the array and are normally displayed as a gray-shaded image where white corresponds to a count of 256 and represents a radiance of 0. In the same fashion a brightness count of 0 is displayed as black and represents the highest (warmest) radiance values. Table 4 shows the character assigned to each brightness count interval and the celsius temperature range of that interval.

The cloud top temperature can be used to determine the approximate height of the cloud top with *a priori* knowledge of the vertical atmospheric temperature profile at the location of the cloud, and taking into account the distance correction discussed earlier. For this study no attempt is made to define a specific cloud layer. To demonstrate the comparison technique, brightness count intervals were chosen to simply

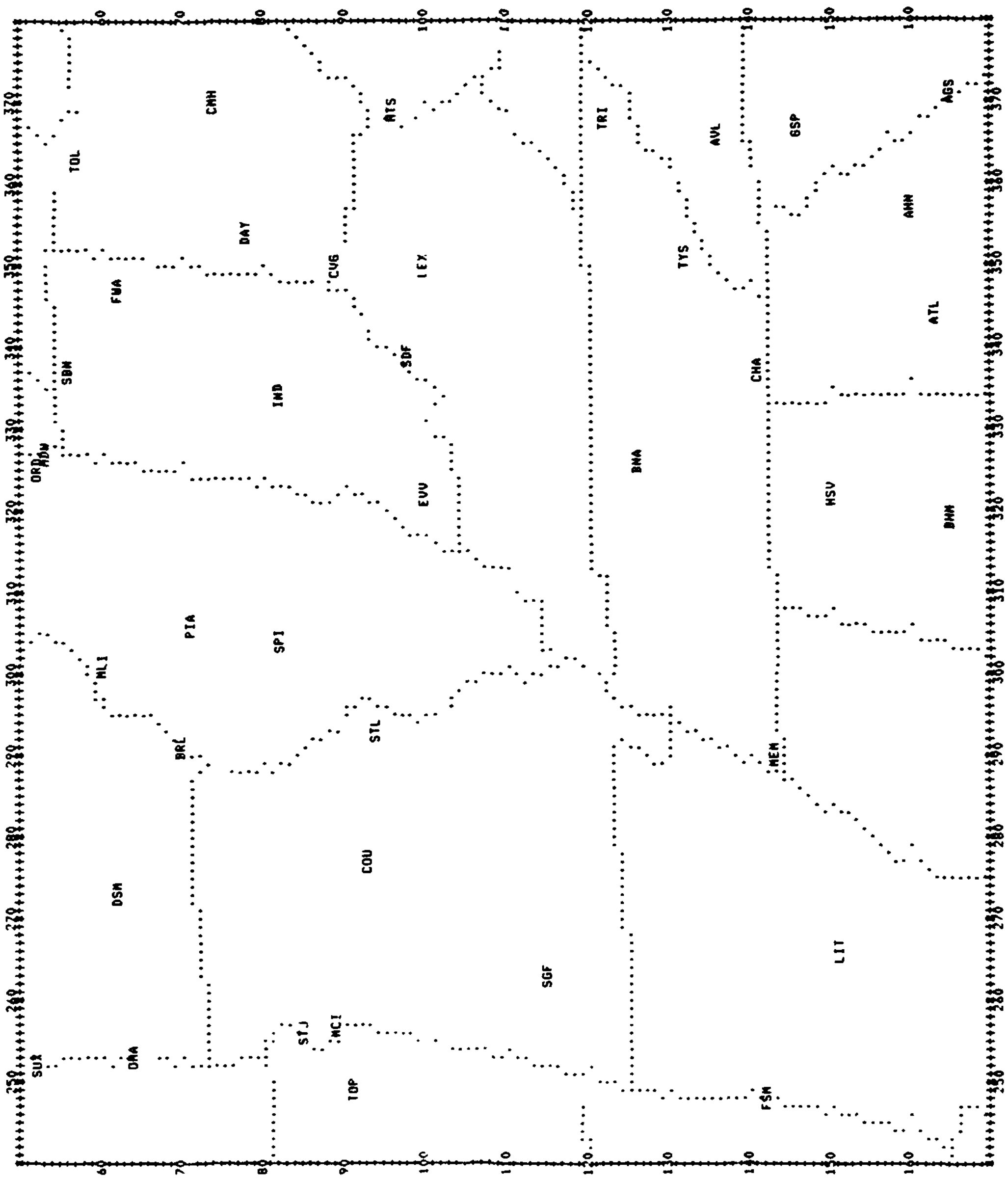

Figure 15. Example of MOS data coverage.

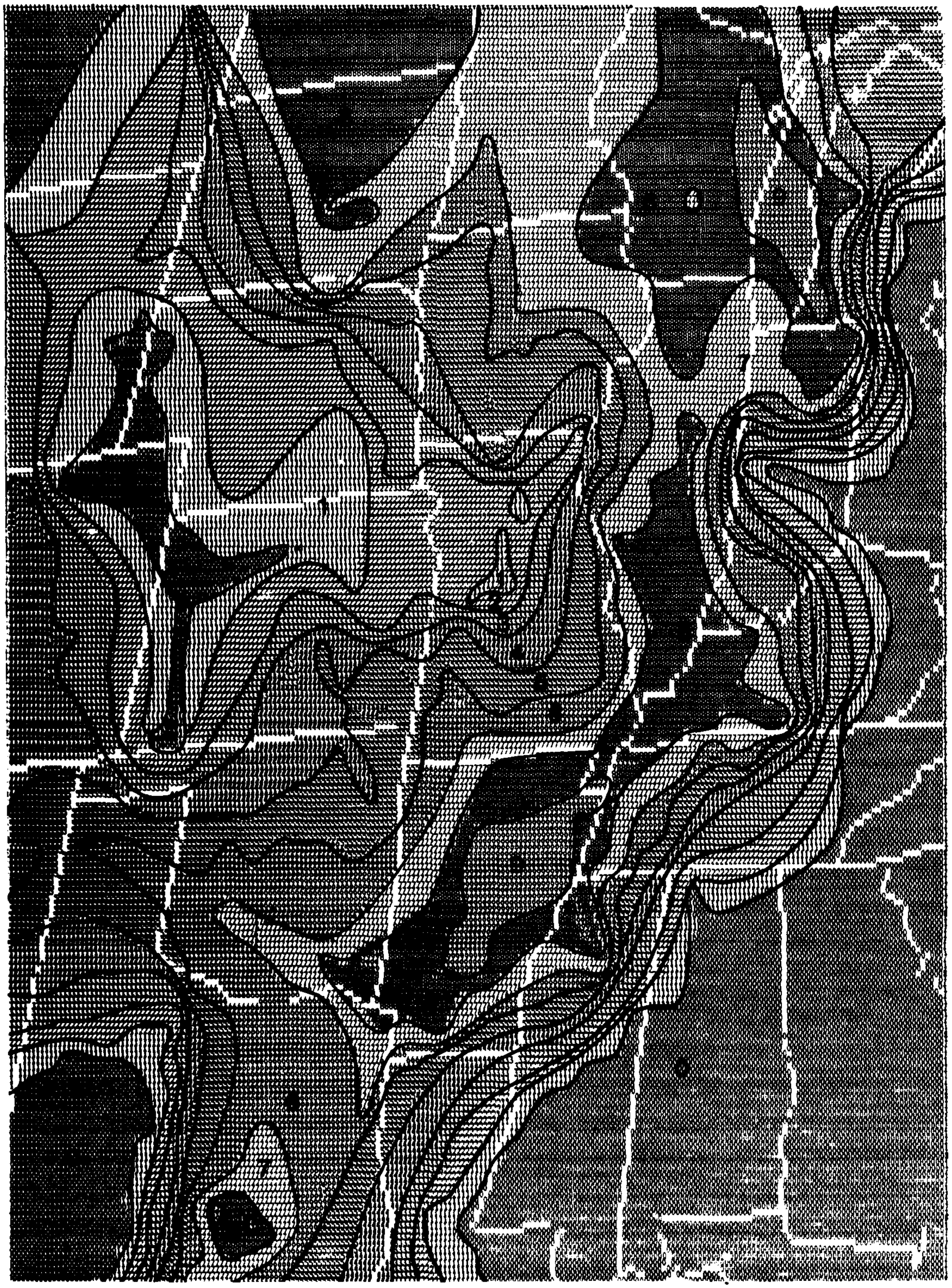

Figure 16. Sample of estimated satellite product (ESP).

Table 4

Infrared 'Brightness Count' intervals. Also shown are the letters used to represent them on the satellite data displays.

Brightness Counts		Symbol
1 - 10	=	A
11 - 20	=	B
21 - 30	=	C
31 - 40	=	D
41 - 50	=	E
51 - 60	=	F
61 - 70	=	G
71 - 80	=	H
81 - 90	=	I
91 - 100	=	J
101 - 110	=	K
111 - 120	=	L
121 - 130	=	M
131 - 140	=	N
141 - 150	=	O
151 - 160	=	P
161 - 170	=	Q
171 - 180	=	R
181 - 190	=	S
191 - 200	=	T
201 - 210	=	U
211 - 220	=	V
221 - 230	=	W
231 - 240	=	X
241 - 250	=	Y
251 - 260	=	Z

identify cloud masses which fall into a temperature range, making the assumption that they will be of like origin and type. This assumption, though not always valid, is similar to the contouring technique used to display IR satellite imagery that is used operationally at NWS and AWS forecasting facilities.

As mentioned earlier, each letter on the satellite display (Figure 7) represents one pixel and approximately a 10 km x 10 km sample. Unlike the ESP and OBS, no interpolation of data was necessary. Referring to Table 4, brightness counts on the imagery used in this study ranged from 'G' to 'U' which corresponds to a temperature range of $26^{o}C$ to $-65^{o}C$ (see also Table 7).

2.3.4 'Bridges'

One of the data processing steps tested in the present study was an approach to the problem of quantitatively and objectively comparing the digital satellite data with products (such as an ESP) determined from forecast model output data. Such a method is termed a 'bridge'.

There are numerous methods for determining and describing the motion of a cloud field that range in complexity from a visual appraisal of successive cloud field images to routines that fit a geometric shape such as an ellipse to the cloud field and track its centroid (Haass, 1981). For the scope of this study several routines were developed to form the 'bridge' that take advantage of the data processing capability of the VAX 11/780 computer at CSU, yet easily adapt to an interactive display processor.

The bridge display used most frequently in our study shows the vertical or horizontal axis of the center of a cloud mass on an ESP or satellite display. This display will allow the forecaster to see how the satellite and ESP cloud masses 'match up' and a sequence of displays will give a graphic depiction of lateral movement. The locations of the cloud mass axis along each row or column of the satellite or ESP array can also be stored, and compared, to compute the rate of translation.

The routine to compute the bridge display will locate centers along each row or column with the letter that corresponds to the satellite category, and the number that corresponds to the ESP category, when either is above a threshold value specified by the operator. For example Figure 17 shows a bridge of ESP values greater than 7 and

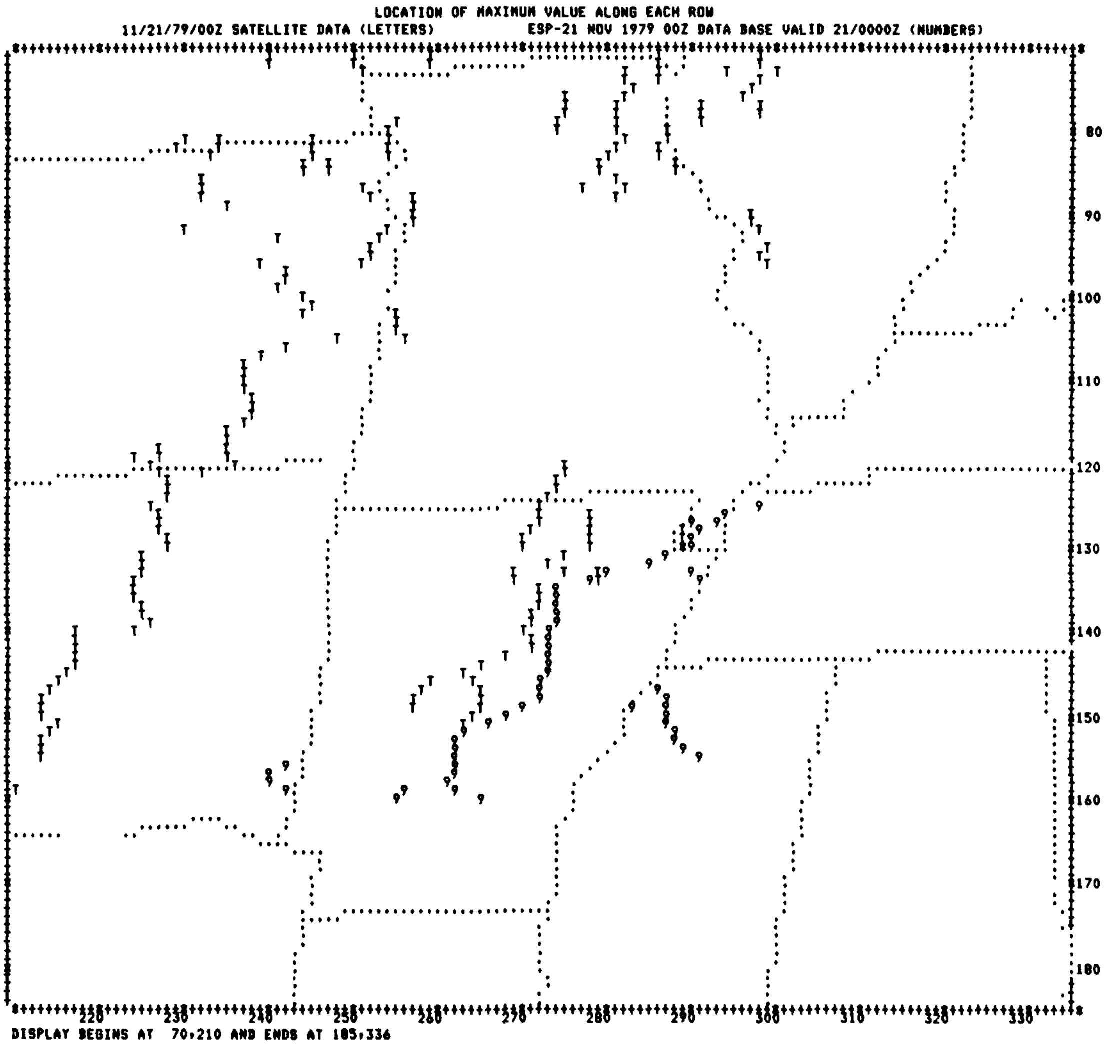

Figure 17. A 'bridge' display. Letters represent the location of a center of a satellite cloud field along a row of data, numbers give a similar display of ESP data.

satellite values greater than 'R'. Another display developed for this study is a simultaneous display of the satellite data, the ESP, and a bridge (Figure 18). This display covers a smaller geographical area, and allows the forecaster to specify the geographical boundaries of the satellite and ESP categories to display. (This display was found to be the most useful for locating and comparing centers of action in the two cloud fields).

2.3.5 '<u>Britecount</u>'

The bridge routine adequately describes the movement of the cloud mass center, but does not account for uneven expansion or the dynamic growth or decay rate. To aid in monitoring movement of this type a data processing routine was developed to graphically display the values of each array element along a row or column (Figure 19). By tracking the movement of maxima and minima along a row of data, the forecaster can monitor lateral movement as in the bridge display. At the same time growth or decay of a cloud mass along a row or column of data can be monitored by the change in 'width' of a given value on the graph. For example, the bridge display may show the center of a cloud field moving east at 5 pixels per hour, while it is actually expanding laterally and the eastern edge is expanding at a faster rate than the western edge. The 'britecount' display would show not only how the center of the cloud mass was moving but would also show the expansion and may show an eastward movement of only 4 pixels per hour.

Up to four profiles are displayed on each printout with the horizontal axis representing a row or column of the data display. The vertical axis of each of the four profiles represent +/-15 categories from the horizontal axis. For example a range of brightness counts of

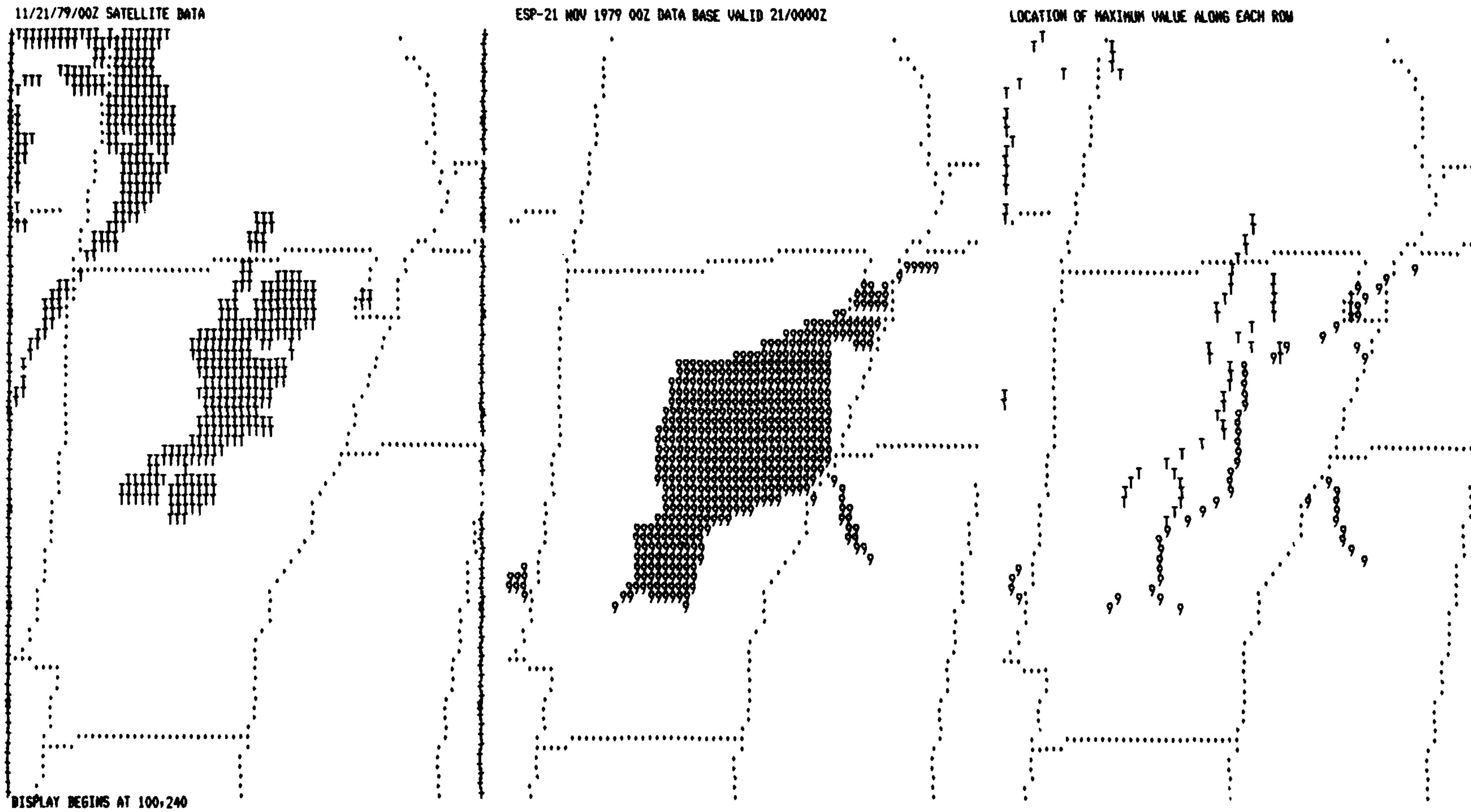

Figure 18. Combined display of satellite, ESP, and bridge. Bridge is a display of satellite fields greater than 'S', and ESP fields greater than '9'.

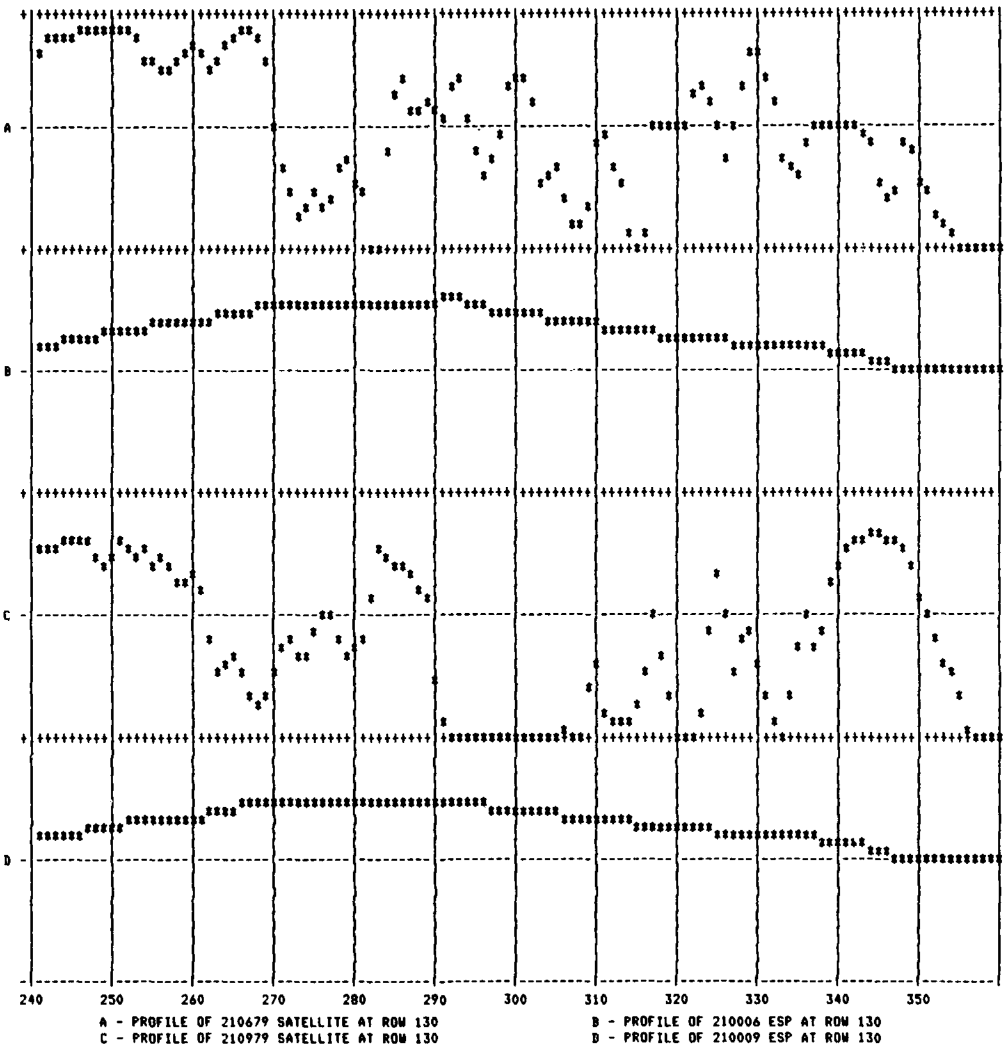

Figure 19. Profile of satellite and ESP at 21/03Z and 21/06Z.

115 to 205 was chosen at line 'A' (Figure 19). The line at 'A' represents 160 and the profile is a graph of brightness counts that fall in the range 115 to 205. Locations with values above 205 are displayed as 205 and those below 115 are displayed as 115.

Since an ESP only contains 9 categories the horizontal axis will represent '0' and the data will be displayed as +9 values above the line (Graph B, Figure 19).

The movement of a cloud field can be determined from a sequence of britecount displays. The britecount display can be used to display a set of 4 profiles along different rows or columns of the data at a given time, or to display 4 profiles of a single row or column over a sequence of time periods. By selecting rows and columns through the center of the cloud field, the components of the meridional and latitudinal displacement can be used to compute a vector that represents the cloud field movement.

2.3.6 <u>Contouring</u>

Another feature of the COMTAL data processing and display unit that lends itself to monitoring the movement of cloud fields is the use of graphic planes to store the outline of a specific cloud field. Graphic planes, like those used to overlay state boundaries or titles on the satellite and ESP imagery can also be used to store one or more fields. For example the portion of a satellite image that is greater than category 'S' can be stored on a separate graphic in a unique color and then compared to a graphic containing a category 'S' cloud field from the succeeding hourly image to show the movement of that particular field. Figure 14 shows cloud fields taken from the November 20, 1979

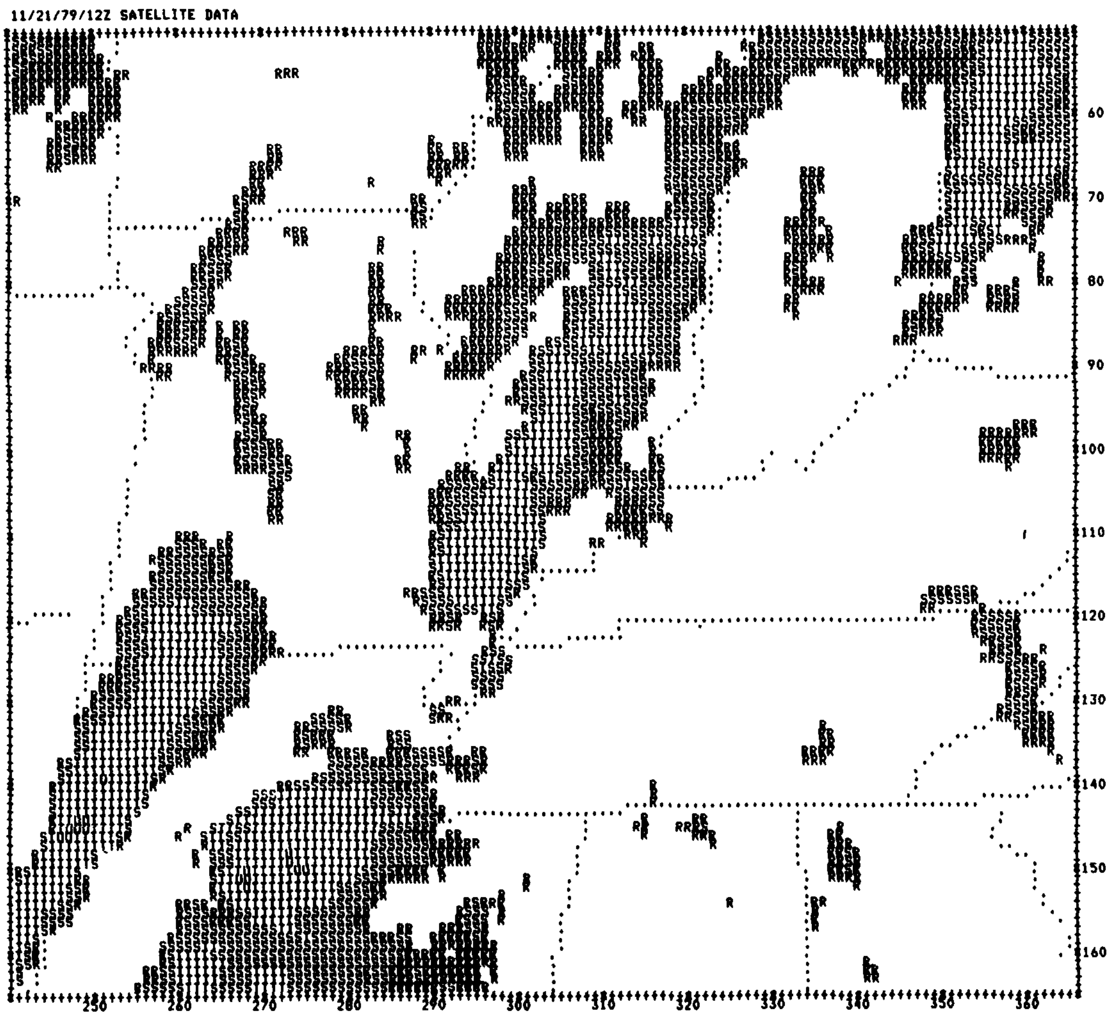

Figure 20. 'Threshold' of satellite image display. Shows values greater than 'Q'.

2100Z and 2200Z images with red the 21Z position and green the 22Z and the darker shade indicating where the two areas overlap.

2.3.7 Thresholding

To single out specific cloud fields in the hard copy displays a routine was developed for this study to threshold a given cloud field category or several categories on the satellite or ESP displays. Figure 20 is an example of a threshold display of satellite cloud fields in category 'R' or higher. The routine allows the forecaster to select a value to threshold, and the geographic area to display.

3.0 CASE STUDY

A two day period in November 1979 was selected to use as a demonstration of the forecast adjustment method shown in Figure 1. The month of November was chosen because of the high frequency of major mid-latitude cyclone occurance and the intent to test by monitoring a transient system vs. a convective cloud field that would be more common in the summer months. Another consideration in the choice was that the models are presumed to have more difficulty handling a developing early winter cyclone and thus would provide a good example for the study. The dates selected for the study were the 20th and 21st of November, 1979.

3.1 Synoptic Situation

A winter storm moved across the midwest from the 19th through the 22nd, with the heaviest precipitation and most widespread cloud cover over the region outlined in Figure 7.

3.2 Data

3.2.1 ESPs

ESPs were constructed for the period from 20/1800Z to 21/1800Z at 3 hour intervals to select cloud fields upon which to focus the method. Figures 21 through 31 show the forecast and observed cloud fields. Table 5 again lists the colors associated with each ESP category. Figures 21, 23, and 24 are produced from the 20/1200Z data base MOS and represent the 6, 9, and 12 hour forecasts (the 9 hour forecast is an

Figure 21. 20/1800Z ESP.

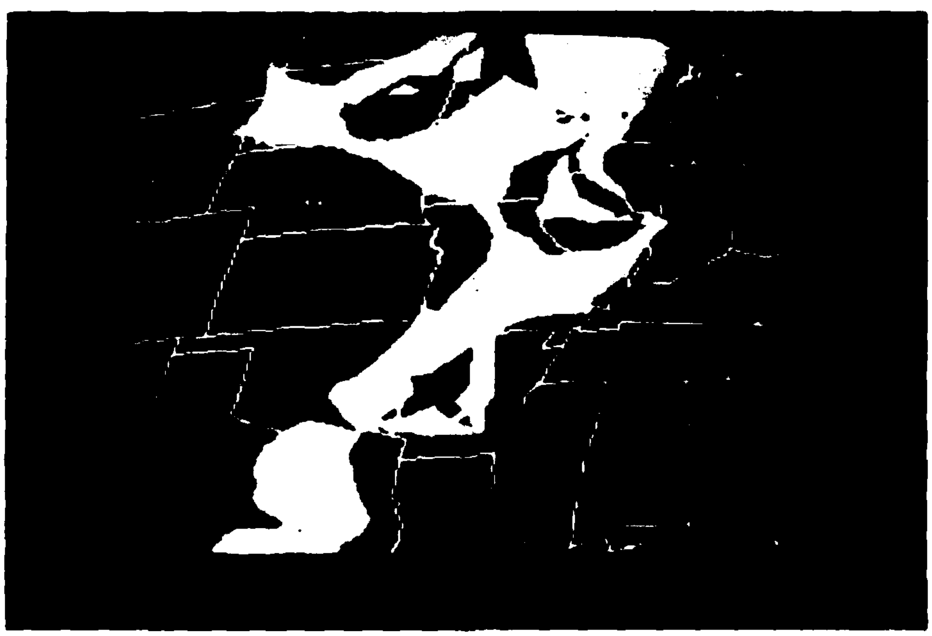

Figure 22. 20/1800Z observed cloud fields (OBS).

Figure 23. 20/2100Z ESP.

Figure 24. 20/2400Z ESP (12 hour forecast from 20/1200Z).

Figure 25. 21/0000Z OBS.

Figure 26. 21/0300Z ESP (persistence probability forecast).

Figure 27. 21/0600Z ESP.

Figure 28. 21/0600Z OBS.

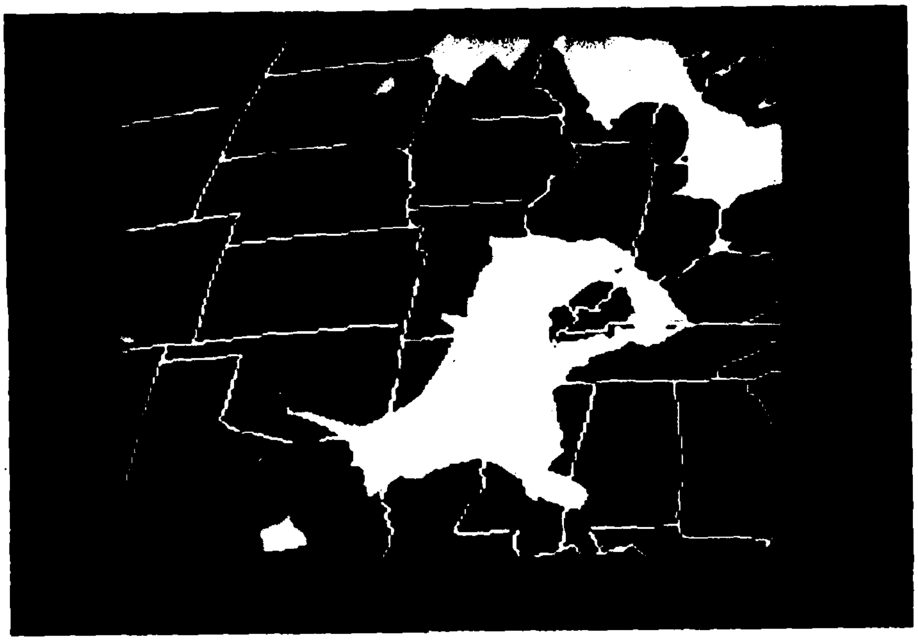

Figure 29. 21/0900Z ESP.

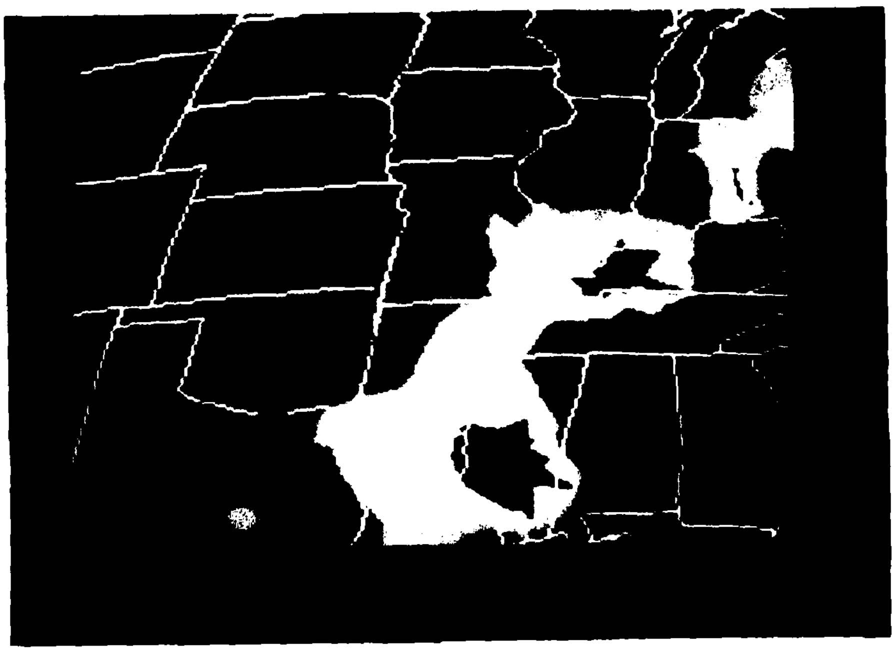

Figure 30. 21/1200Z ESP.

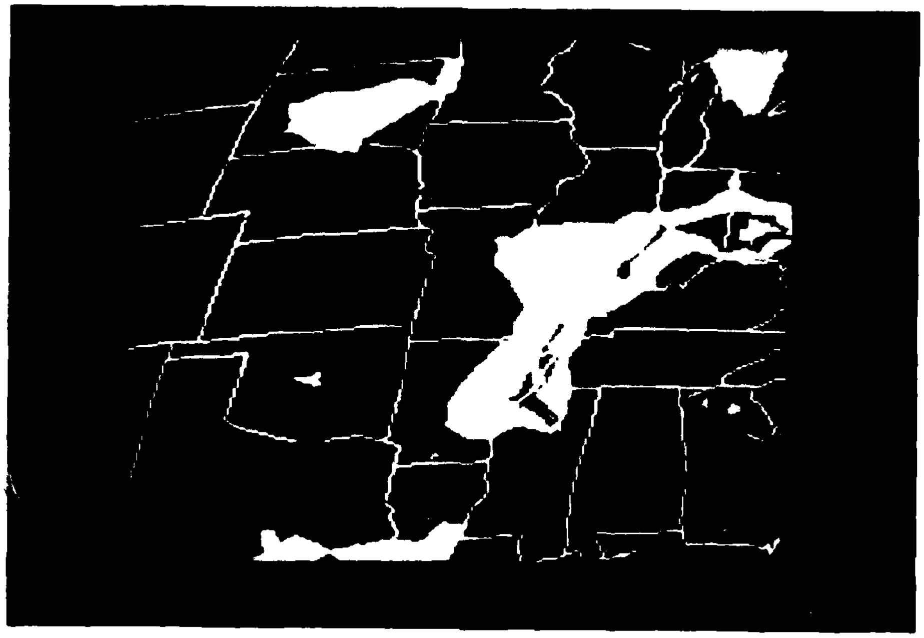

Figure 31. 21/1200Z OBS.

Table 5

Colors Used to Represent Ceiling Categories on ESP's

ESP Number	ESP Color	Cloud Category
9	Lt Green	> 7500 OVC
8	Dk Green	> 7500 BKN
7	Yellow	3000 - 7500 OVC
6	Mustard	3000 - 7500 BKN
5	Lt Brown	1000 - 2900 OVC
4	Dk Brown	1000 - 2900 BKN
3	Lt Maroon	500 - 900 OVC
2	Dk Maroon	500 - 900 BKN
1	Lt Blue	200 - 400 OVC/BKN
0	Dk Blue	SCT - Clear

SCT = 2-5 Tenths BKN = 6-9 Tenths OVC = 10 Tenths interpolation of the 6 and 12 hour values at each station). Figures 25 through 31 represent MOS data from the 21/0000Z data base and observed cloud fields on the 21st.

3.2.2 Satellite

Satellite data were received at the CSU site and stored as an array covering the central one-third of the U. S. The array contains 240 x 240 pixels displayed in the alphabetic categories described earlier. Images obtained include hourly data from 20/1800Z through 21/1800Z except the image at 21/0100Z which was not collected due to hardware problems. The digital satellite data were processed on the VAX 11/780 and stored as image arrays for display on the printer or COMTAL, or as input to the bridge or britecount routines. Figures 32 through 38 show the corresponding satellite images to the 3 hour intervals on which the ESPs and OBS were produced. Table 6 lists the colors assigned to the satellite effective temperature categories.

3.2.3 Comparison of ESP and OBS

To see how well the MOS forecast matched the verifying observations the ESP and OBS displays were compared at 20/1800Z, 21/0000Z, 21/0600Z and 21/1200Z. By comparing Figure 21 with Figure 22 one can see a discrepency in the forecast cloud fields vs. the observed cloud fields. The six hour forecast valid at 20/1800Z shows the same category over southeastern Iowa and central Illinois with another area in eastern S. Dakota and over Arkansas. The ESP valid at 21/0000Z (Figure 24) shows a similar trend as the higher cloud category has moved into northern Illinois and Indiana, while the verifying observations show that same cloud category displaced to the north and also to the south and

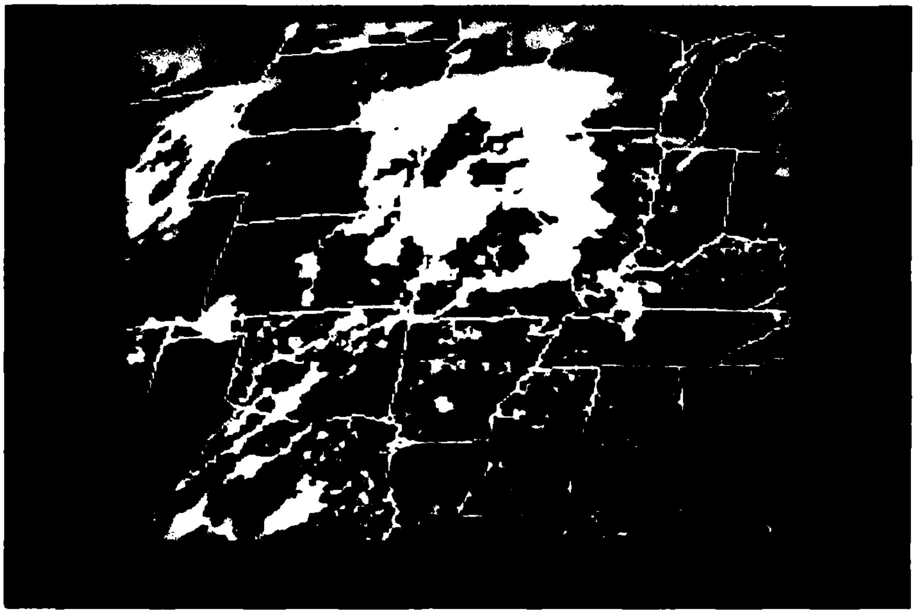

Figure 32. 20/1800Z satellite image.

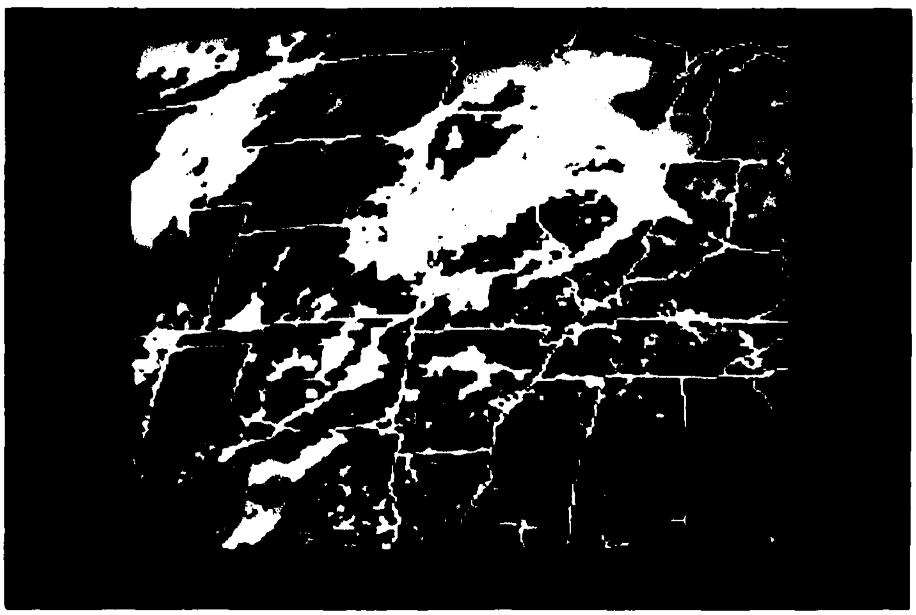

Figure 33. 20/2100Z satellite image.

Figure 34. 21/0000Z satellite image.

Figure 35. 21/0300Z satellite image.

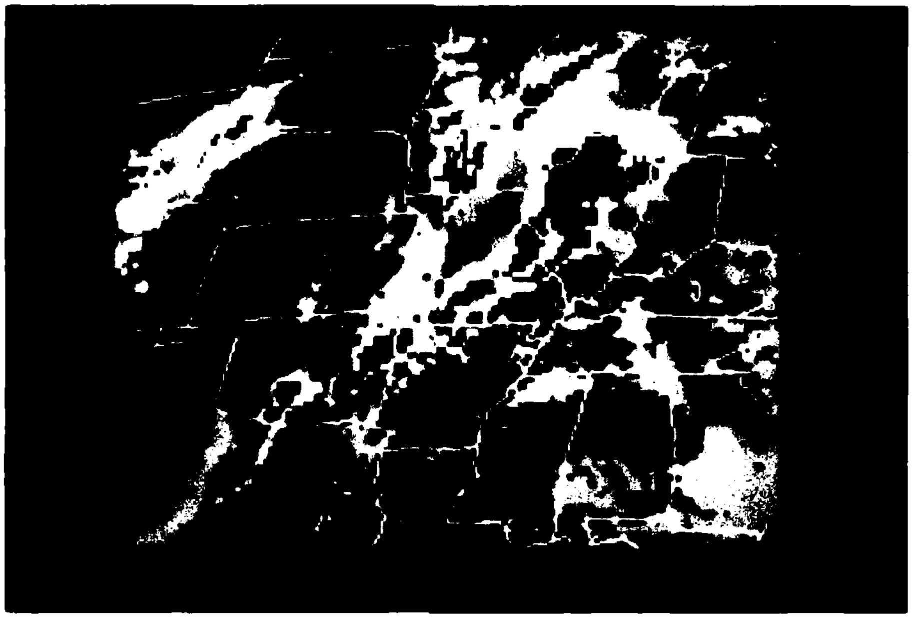

Figure 36. 21/0600Z satellite image.

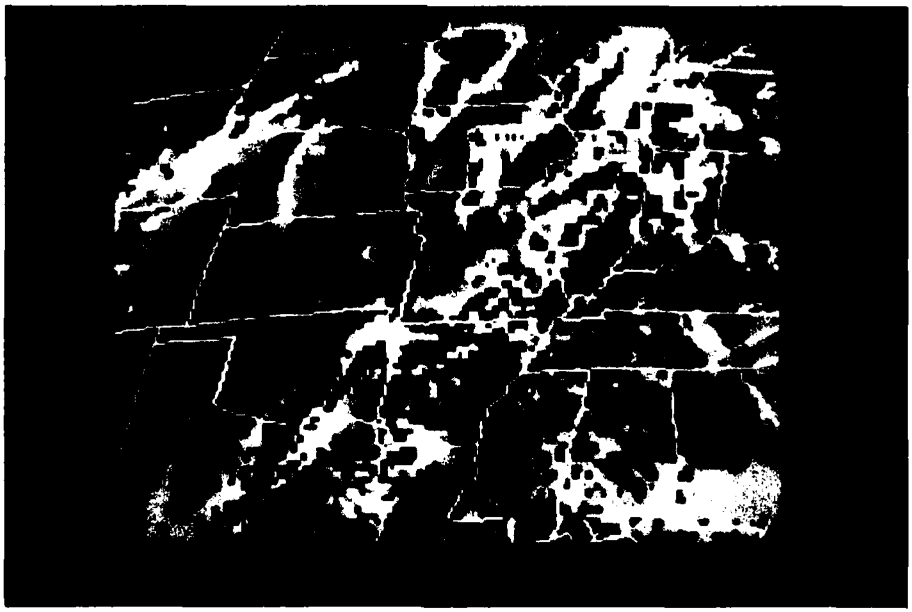

Figure 37. 21/0900Z satellite image.

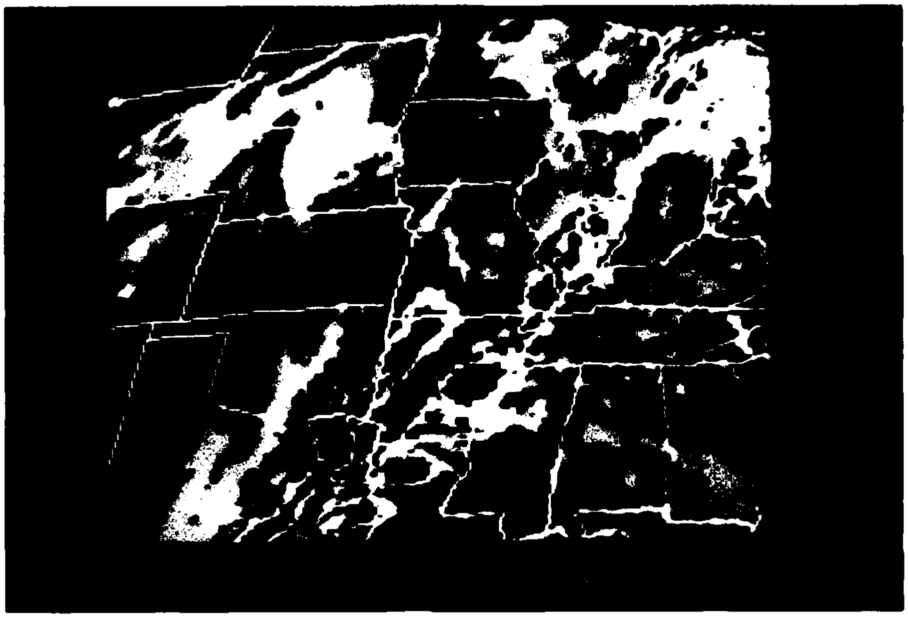

Figure 38. 21/1200Z satellite image.

Table 6

Colors assigned to the satellite brightness count categories on the following images (Figures 32-38).

Brightness Counts	Symbol		Color	Approx. Temp. (C)
61 - 70	=	G	Black	26 to 22
71 - 80	=	H	Black	21 to 17
81 - 90	=	I	Dk Grey	16 to 12
91 - 100	=	J	Md Grey	11 to 7
101 - 110	=	K	Lt Grey	6 to 2
111 - 120	=	L	Dk Blue	1 to -3
121 - 130	=	M	Lt Blue	-4 to -8
131 - 140	=	N	Dk Maroon	-9 to -13
141 - 150	=	O	Lt Maroon	-14 to -18
151 - 160	=	P	Dk Brown	-19 to -23
161 - 170	=	Q	Lt Brown	-24 to -28
171 - 180	=	R	Mustard	-29 to -35
181 - 190	=	S	Yellow	-36 to -45
191 - 200	=	T	Dk Green	-46 to -55
201 - 210	=	U	Lt Green	-56 to -65

southwest. Comparing the OBS and ESP displays on the 21st at 0600Z and 1200Z again reveals some discrepancy in the position of the higher cateory cloud fields.

The case study test (using this hindsight) is thus to see if the satellite imagery can be used to detect the apparent error in the MOS cloud forecast and in turn be used to adjust that forecast.

3.2.4 Comparing ESP with Satellite

When comparing an ESP with a corresponding satellite image several possibilities arise:

1. The ESP shows a cloud field and the satellite image does also.
2. The ESP shows a cloud field and the satellite image does not.
3. The ESP shows no cloud fields and the satellite shows no cloud.
4. The ESP shows no clouds and the satellite shows a cloud field.

Looking first at 1, there are again several possibilities. The satellite may be showing the 'same' cloud field or it may be a different field. For example the ESP from MOS may show a field of ceilings less than 3000 feet and the satellite may have a cloud field in the same geograhical region but have brightness values that indicate the field is at a much higher level. In this case the high level clouds may be obscurring the lower level clouds or the low level clouds may be absent entirely.

The scenarios in in 2 and 4 are similar in that the MOS forecast is apparently in error. The cloud fields on the MOS forecast in 2 will need to be adjusted, that is, moved or eliminated, and the MOS forecast in 4 adjustment ammended to include clouds shown by the satellite. The remaining option, 3, appears to be 'no change required' situation. The conclusion, then, is that there must be a subjective forecaster input both to the selection of the cloud fields to monitor and to th decision to adjust or not adjust the forecast in the 6-12 hour time frame.

The data set under study was examined to decide which cloud fields to monitor, as shown in the decision box 'select cloud fields to compare' in Figure 2. Several fields were chosen that fit the 1, 2, and 4 situations listed above.

Figures 40 and 41 show the satellite and ESP for 20/1800Z and Figure 42 shows a bridge display for the same time period. Looking at Figure 42, several things should be noted. There is a region of cloudiness on the ESP over western IOWA (8's), north central Missouri (7's), and over eastern Missouri and Illinois (7's and 8's). Each of these areas are easier to distinguish in their entirety on the ESP (Figure 41). One feature that stands out is the satellite cloud field over Oklahoma and Arkansas with no corresponding field on the ESP.

Looking at the ESP data from the 21st, the cloud field over Arkansas continues to be carried on the 21/0000Z observed cloud cover display (Figure 25) and successive ESP's. The cloud field is an example of two of the possibilities: (a) the cloud field is not forecast by the 20/1200Z, but appears on the satellite imagery by 1800Z (situation 2), and (b) the 21/0000Z MOS forecast picks up the cloud field and the satellite and ESP both show the field in the following six hours of the forecast period (situations 1).

The next step in the comparison procedure (Figure 2) is to select a method of comparison to use in this case study. Because a very large data set is required to develop a statistical bridge, independent movement was selected. To demonstrate this method the cloud mass in Arkansas on the 21/0000Z observed cloud field was chosen.

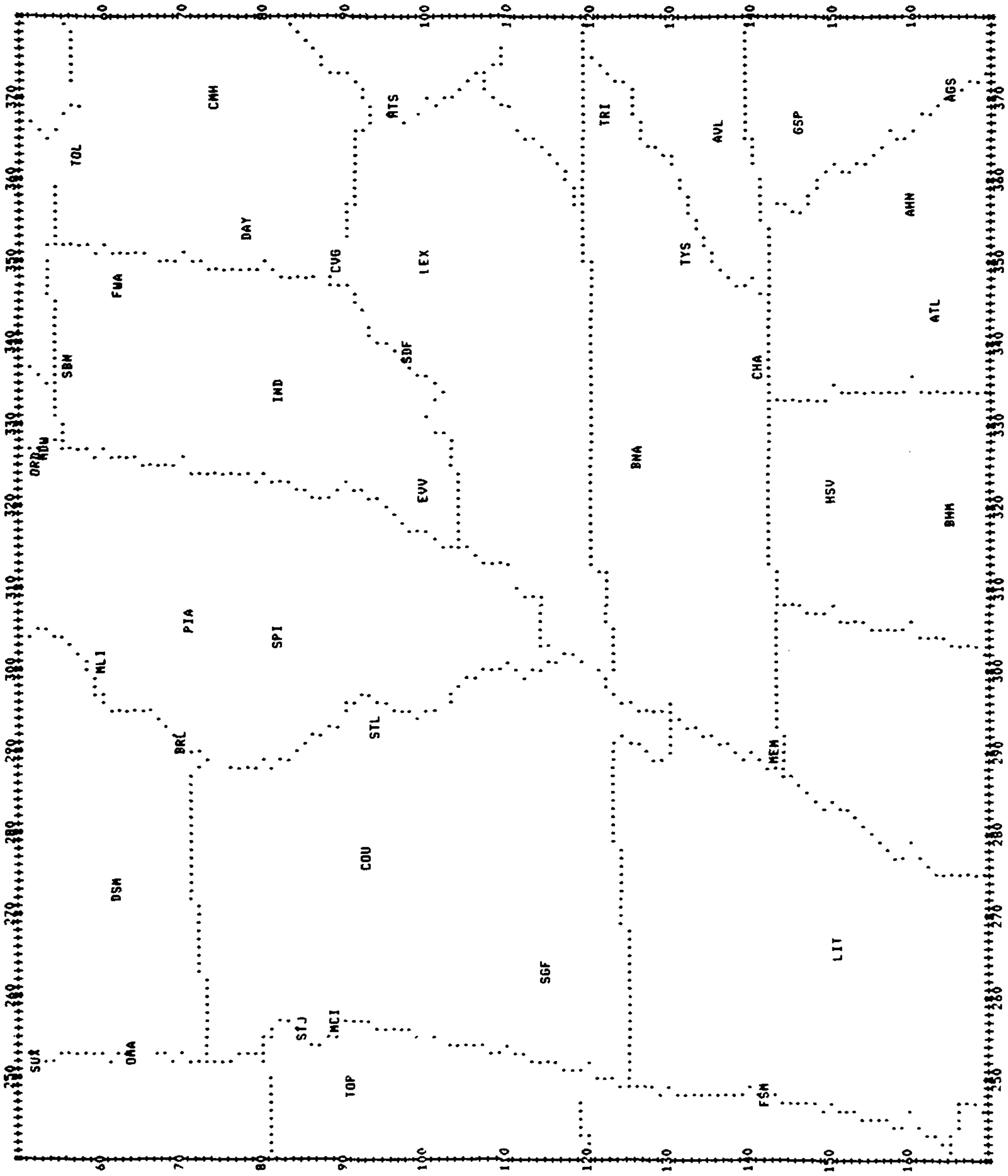

Figure 39. Location of MOS stations.

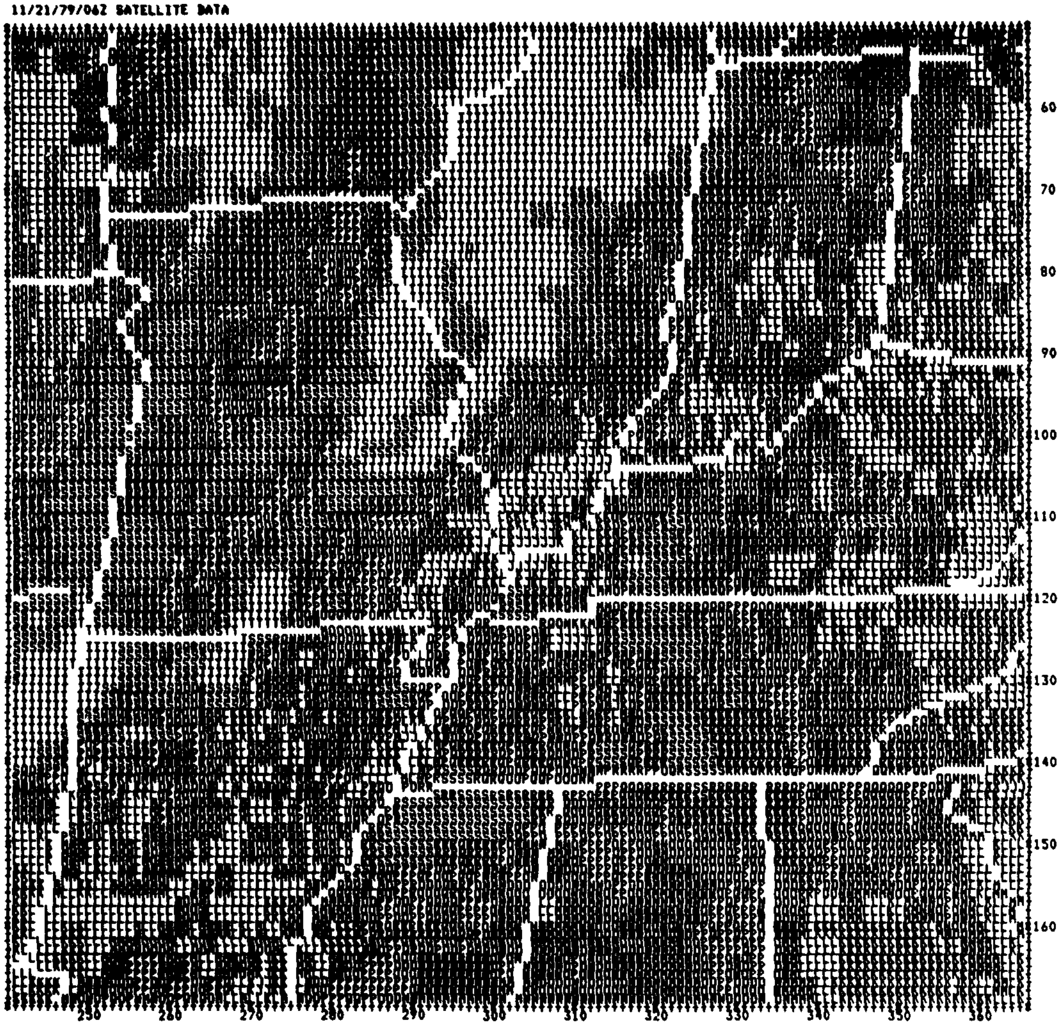

Figure 40. 20/1800Z satellite image.

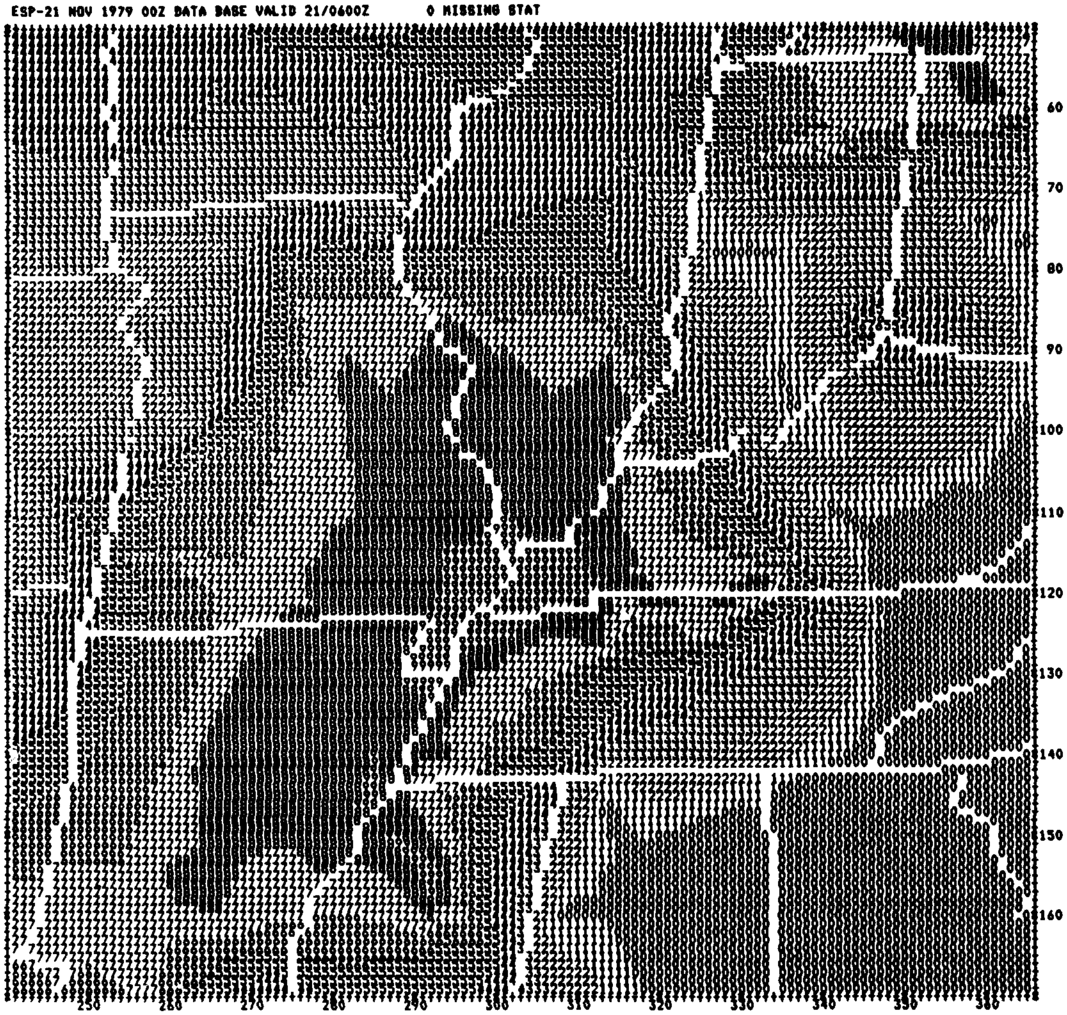

Figure 41. 20/1800Z ESP.

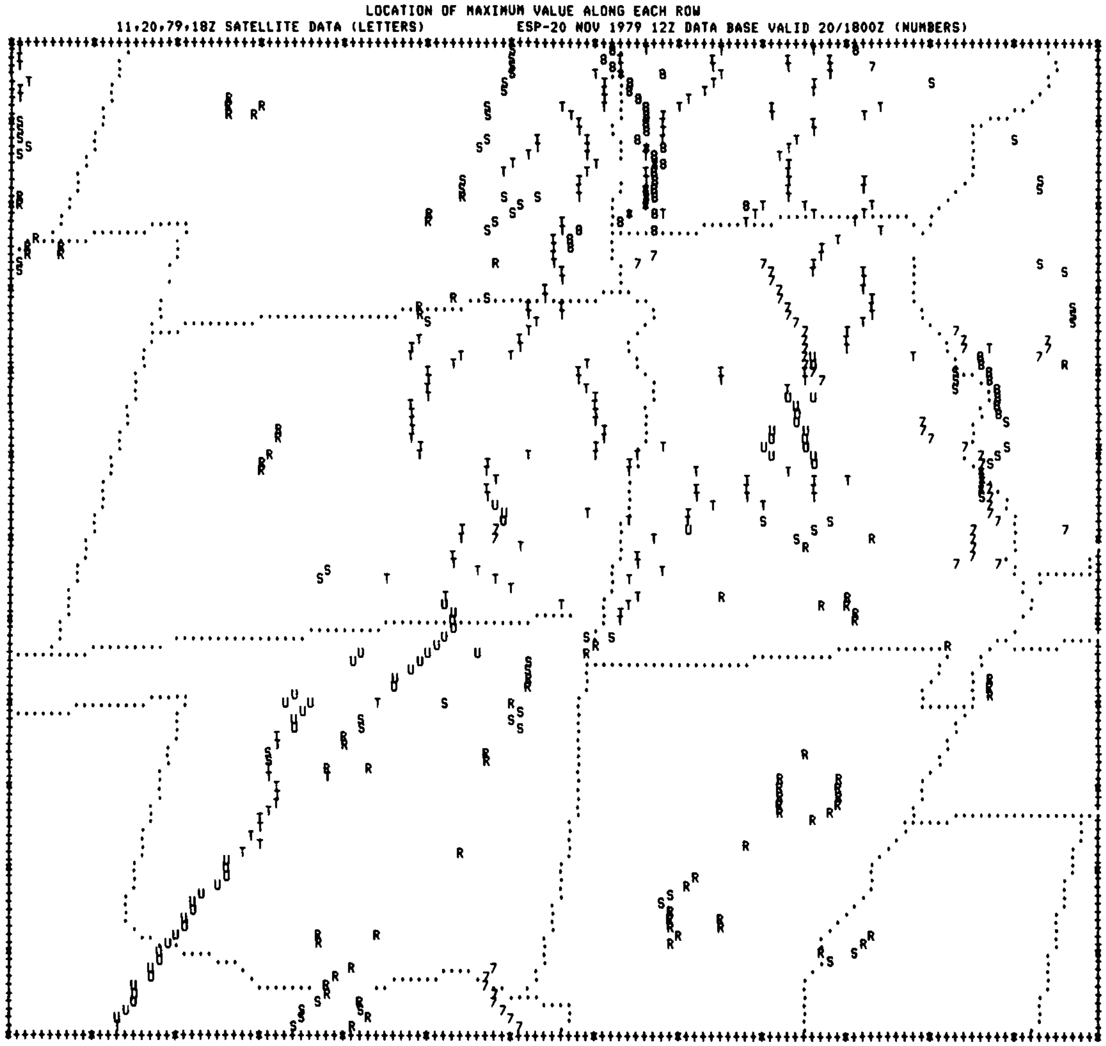

Figure 42. 20/1800Z 'bridge'. Display of satellite values greater than 'Q', and ESP values greater than 6.

A bridge display was run for the initial hour (0000Z) to look for a link between the observed cloud field and the satellite image (Figure 43). Since MOS data would need to be interpolated to produce an ESP at the 7, 8, 9, 10, and would not add new information at this point, a bridge display was then produced at 3 hour intervals. Figures 44-47 show bridge displays at 03Z, 06Z, 09Z, and 12Z. The movement of the satellite and MOS fields appear to differ in that the highest MOS category (9-green) moves into western Kentucky on the 6 hour forecast (Figure 45) and then moves very little on the 12 hour with an area of higher ceilings forecast to develop over Mississippi. The high level clouds on the satellite display move further north into Illinois at 06Z and continue to move into northern Indiana by 12Z. Another area of high cloudiness develops over central Arkansas by 12Z (due apparently to a line of thunderstorms developing ahead of the front).

At this point in the study it became obvious that linking the satellite and ESP cloud fields would not be an easy task, for several reasons. First, the case in which the MOS did not produce a cloud field and the satellite shows that one exists prohibits the calculation of movement to compare to or adjust. This case appears to be common, at least in the data displays used in the study. The flow through Figure 2 then becomes lost at the first subjective point. The second difficulty arises when the cloud fields appear to match as in the case over Arkansas at 0000Z but then the ESP forecast field moves in two separate directions and the satellite image shows that an apparently new field is developing at another location, in this case behind the original cloud field location.

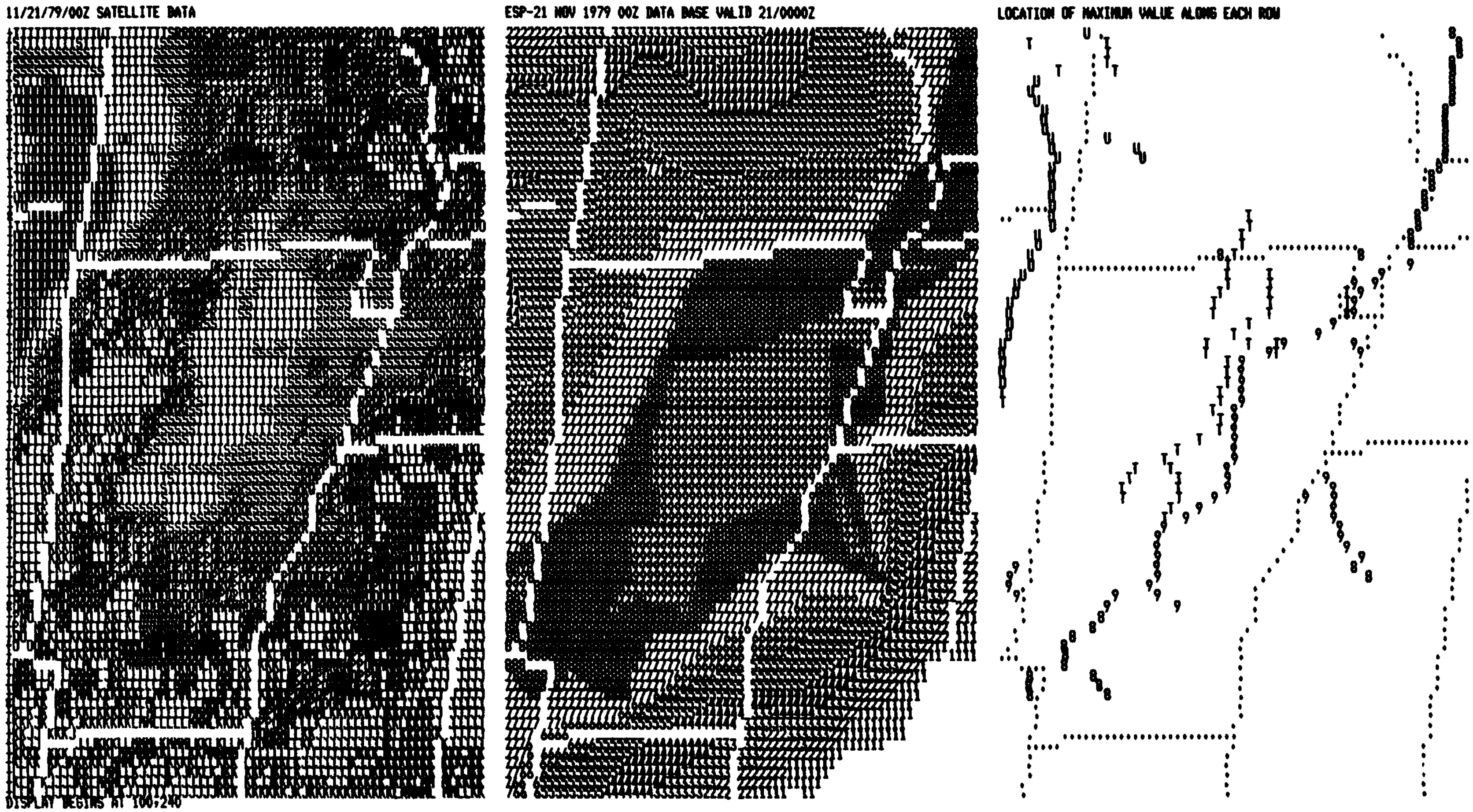

Figure 43. 21/0000Z bridge display.

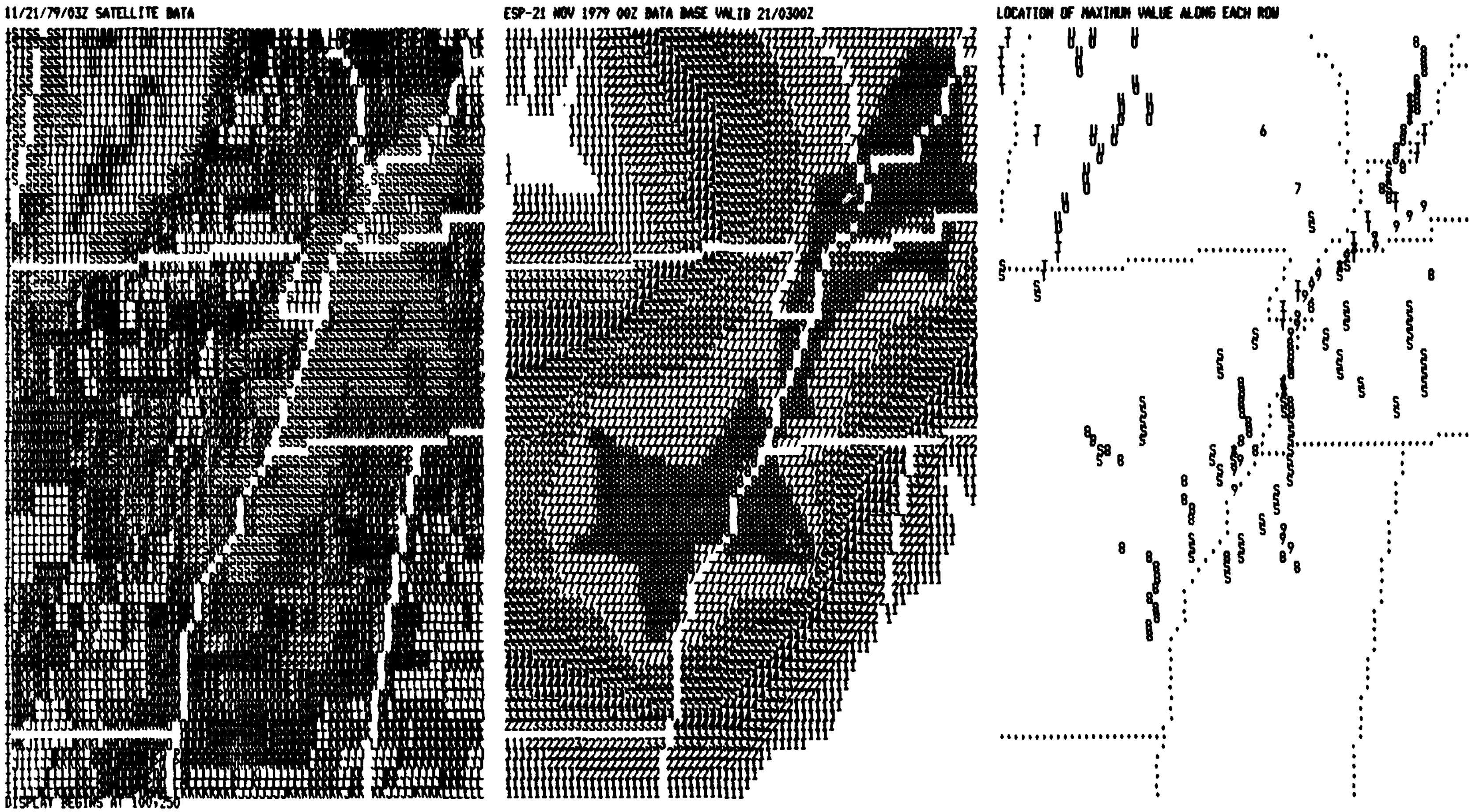

Figure 44. 21/0300Z bridge display.

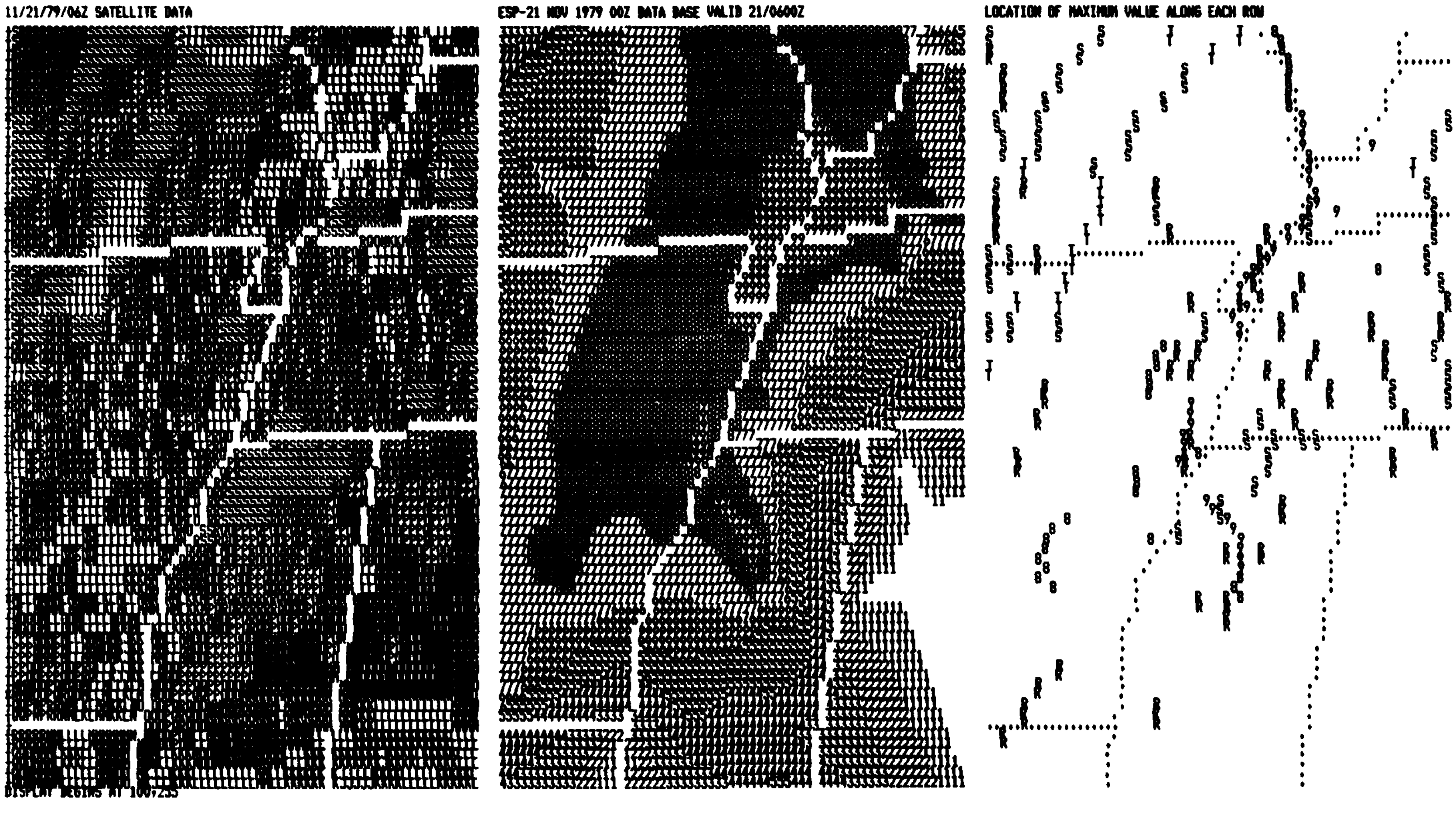

Figure 45. 21/0600Z bridge display.

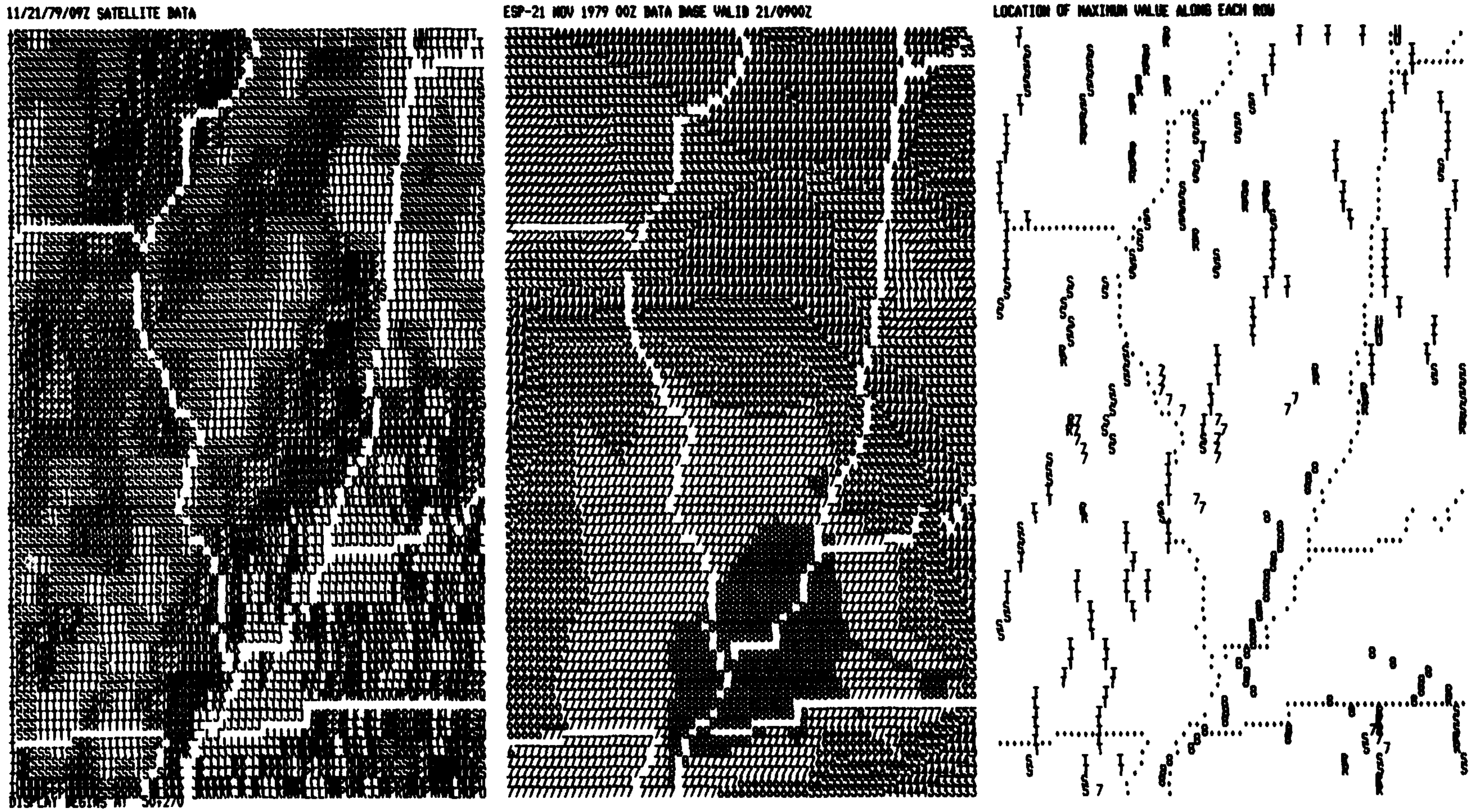

Figure 46. 21/0900Z bridge display.

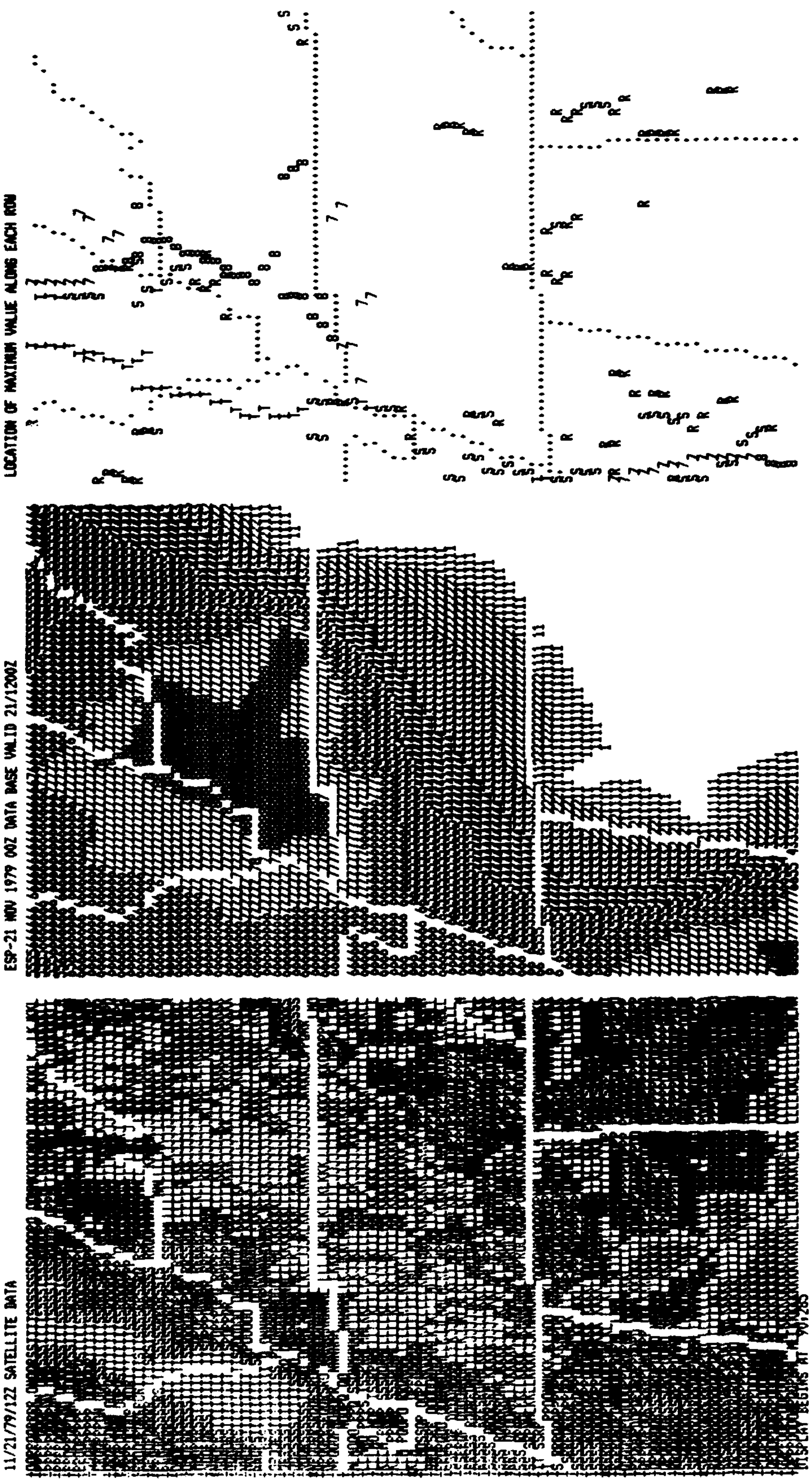

Figure 47. 21/1200Z bridge display.

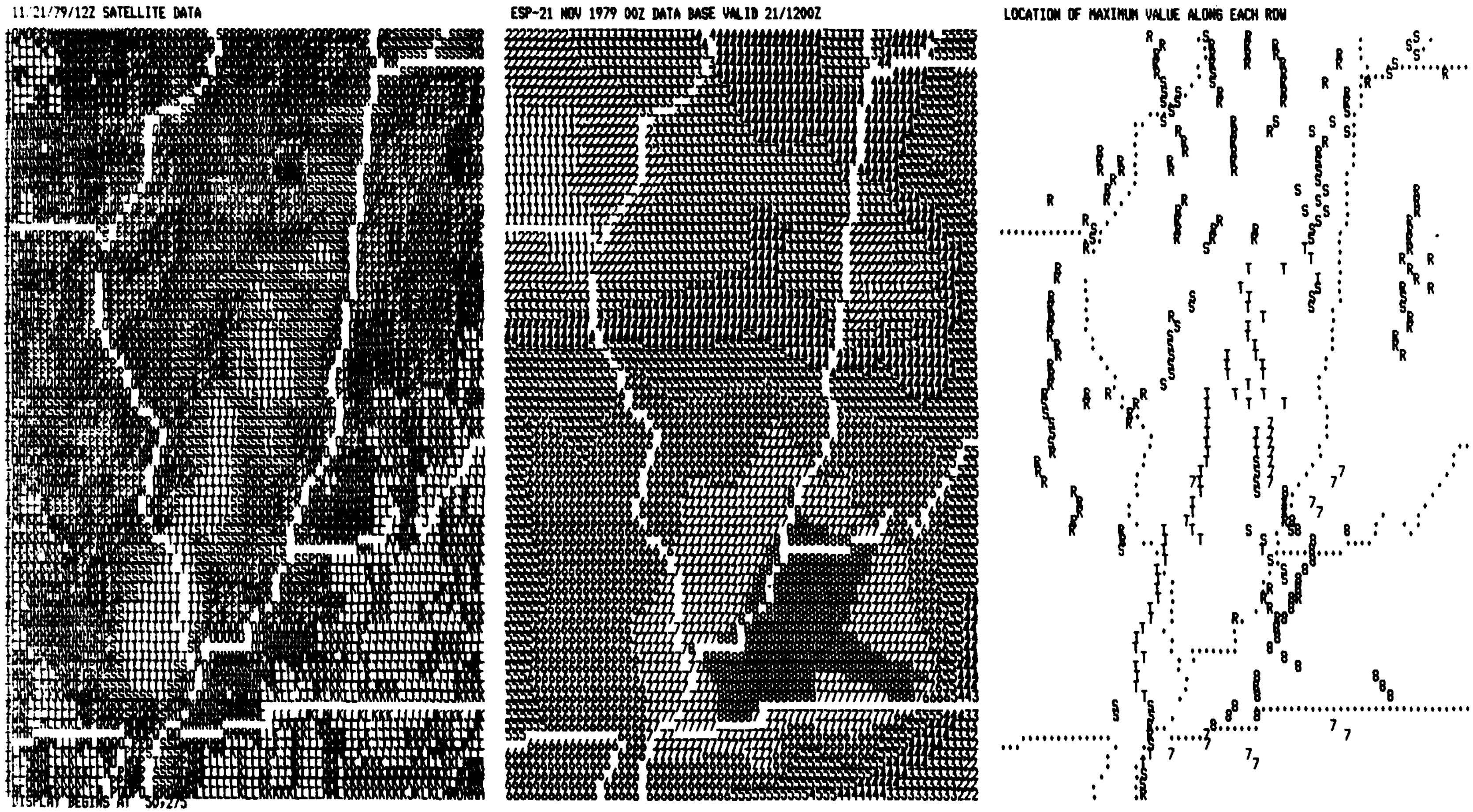

Figure 48. 21/1200Z bridge display.

Continuing on with the test, the cloud field over Arkansas was monitored to see if the satellite data would verify or refute the MOS forecast. Using surface observations the category '9' cloud field on the ESP was matched with the category 'T' field on the satellite image (Figure 43). These represent the 'zero hour' cloud field and would be an indication of which cloud fields can be compared and followed. At 0300Z (Figure 44) a comparison of the fields shows that the 'S' and '8' fields (which in this case are difficult to distinguish from each other) are still in good agreement. The third display at 0600Z shows that the ESP cloud field appears to remain in the same relative location while the satellite field is moving steadily eastward into Tennessee. By 0900Z (Figure 46) the ESP is showing its highest cloud field over the southern tip of Illinois, while the satellite is showing the axis of the higher cloud fields over Missouri and further north into central Illinois an northern Indiana. To the south, the satellite is showing the cloud field that was over Arkansas continuing to spread eastward into Tennessee.

In an attempt to quantify the movement of the cloud fields, a set of britecount displays were produced to determine a movement vector for the cloud mass displayed as 'S' and 'T' on the satellite display and '9' on the ESP (Figure 43). Figures 49 and 50 show a set of profiles produced during the 00Z and 09Z time period along row 130 (Figure 51). Because the ESP data has a range of only 9 values, the profiles of the ESP data does not have a large amplitude, but nonetheless the maximum does show up between columns 286 and 287 at 00Z, and at column 292-293 at 03Z on Figure 49. In contrast the satellite data shows distinct

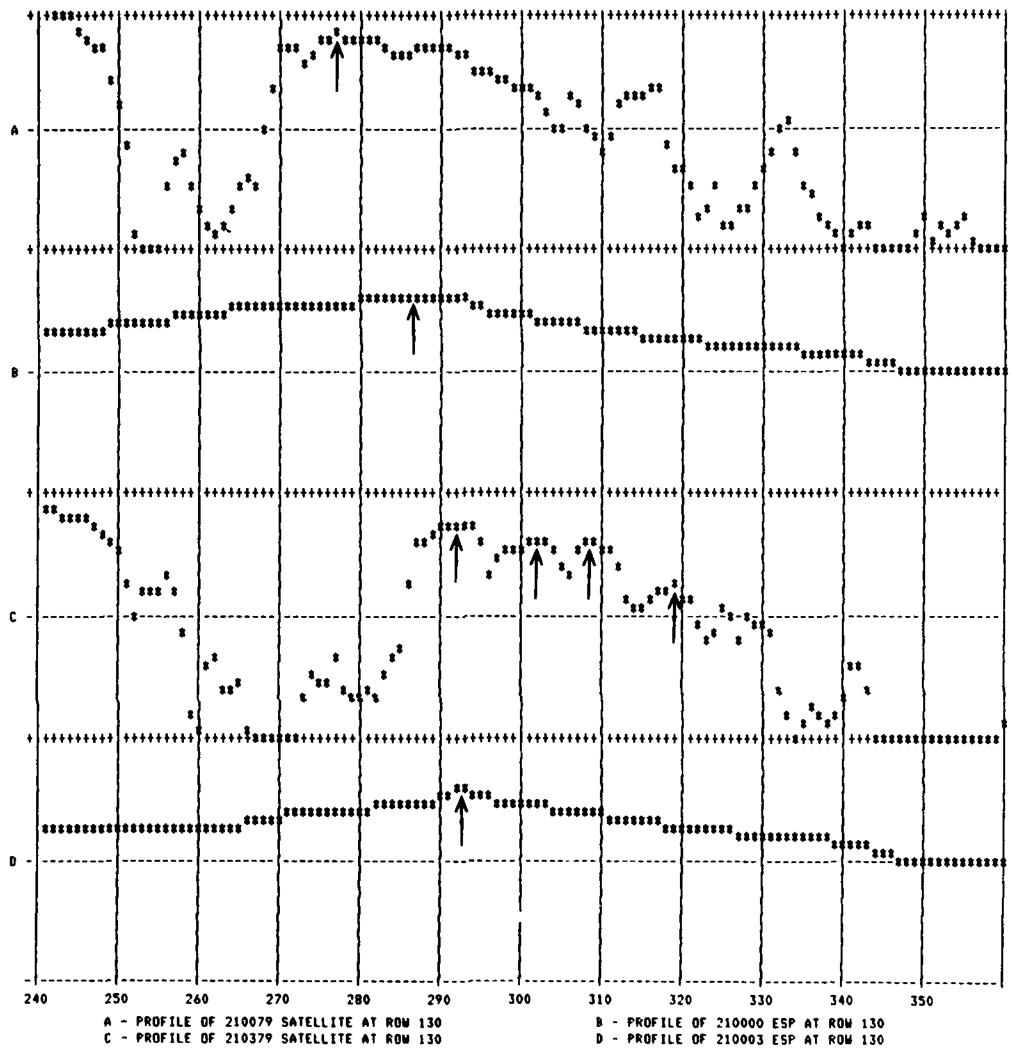

Figure 49. Profile of 21/00Z and 21/03Z satellite and ESP at Row 130.

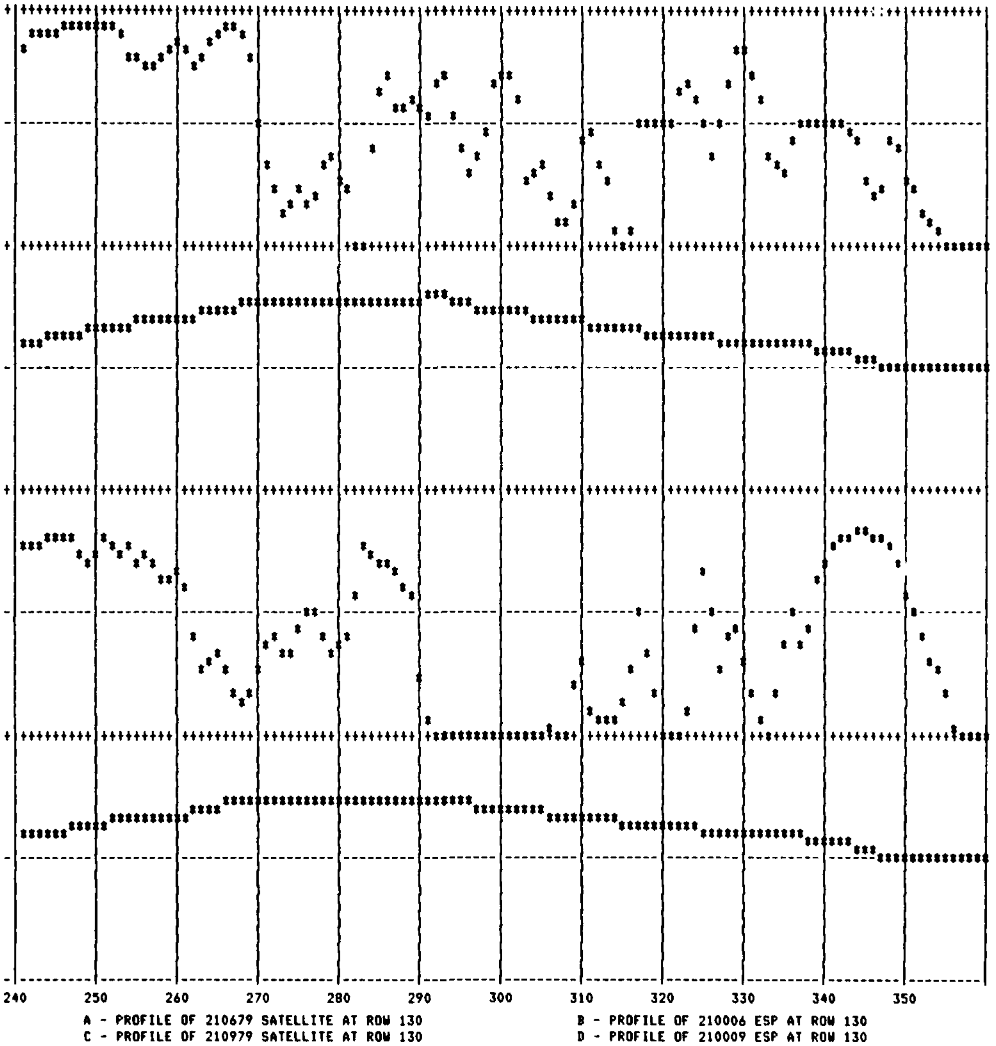

Figure 50. Profile of 21/06Z and 21/09Z satellite and ESP at Row 130.

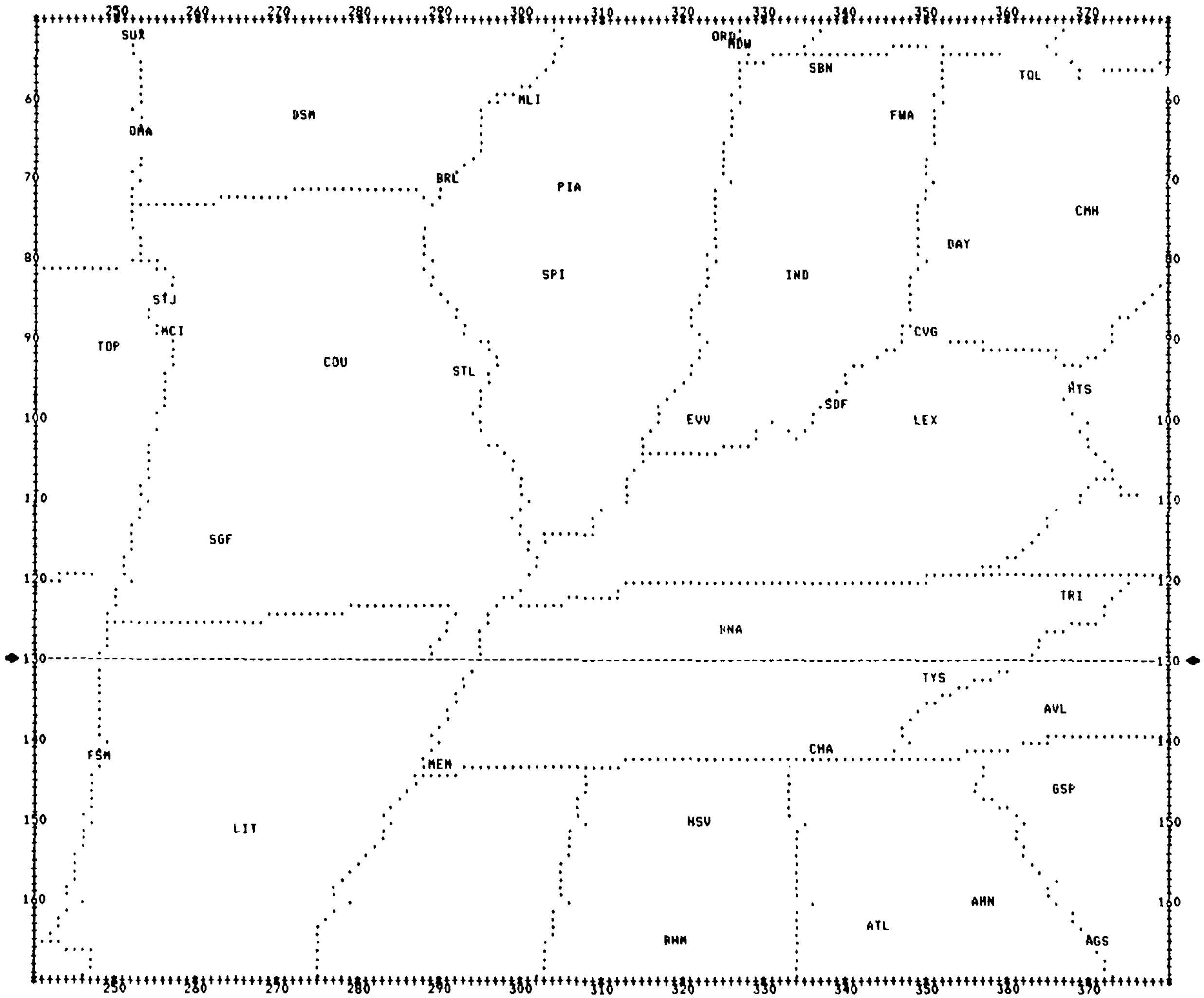

Figure 51. Location of 'Row 130' on data display.

maxima a column 277 on th 00Z data, and columns 292, 302, 308-309, and a lesser max at 319 on the 03Z data.

One advantage of the britecount display can be seen from Figure 49. The profile of the 00Z satellite data (Line A) shows a cloud field maxima extending from column 270 to 291, with a maximum over column 277. Looking only at the bridge display (Figure 45), the center of the cloud field depicted in the right hand panel is in the same place as the max on the britecount display. However the extent of the cloud field is not obvious. As the cloud field grows or shrinks it will be detected on the britecount display, but only the center of the field will be seen on the bridge display.

To demonstrate how 'britecount' shows movement of the satellite field, a display was produced of satellite data only. Figure 52 shows a sequence of 3 hourly profiles along row 130. The movement of the individual maxima are not easily followed, but with the aid of the actual satellite imagery the field with a maximum at column 277 on the 00Z satellite profile can be tracked eastward to column 292 on the 03Z profile, and then the field breaks into several bands on th 06Z profile and appears to form one cloud mass that intensifies on the 09Z profile.

To make a more detailed track of the cloud mass, a set of profiles were run for the 03Z-10Z time period at one hour intervals (Figures 53-54). The movement of the cloud fields becomes more evident by tracking the movement of the cloud that appears at column 290-294 at 03Z (Row A) and moves to the positions marked with an arrow at 04Z through 10Z. Note the rapid development of the field from 08Z on.

The next step in the scheme would be to 'bogus' or produce an adjustment to the forecast. As mentioned previously this is not a

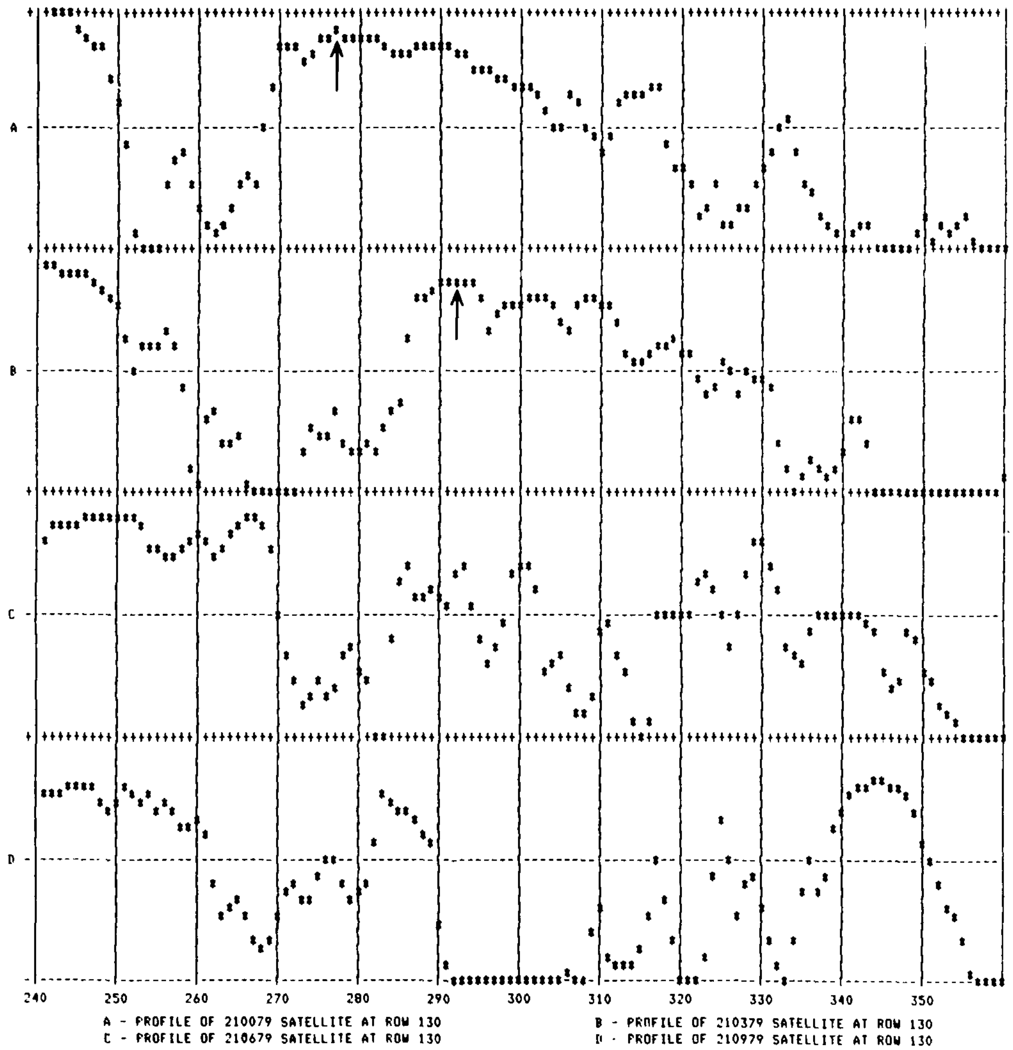

Figure 52. Profile of 21/00-21/09Z satellite data at 3 hour intervals.

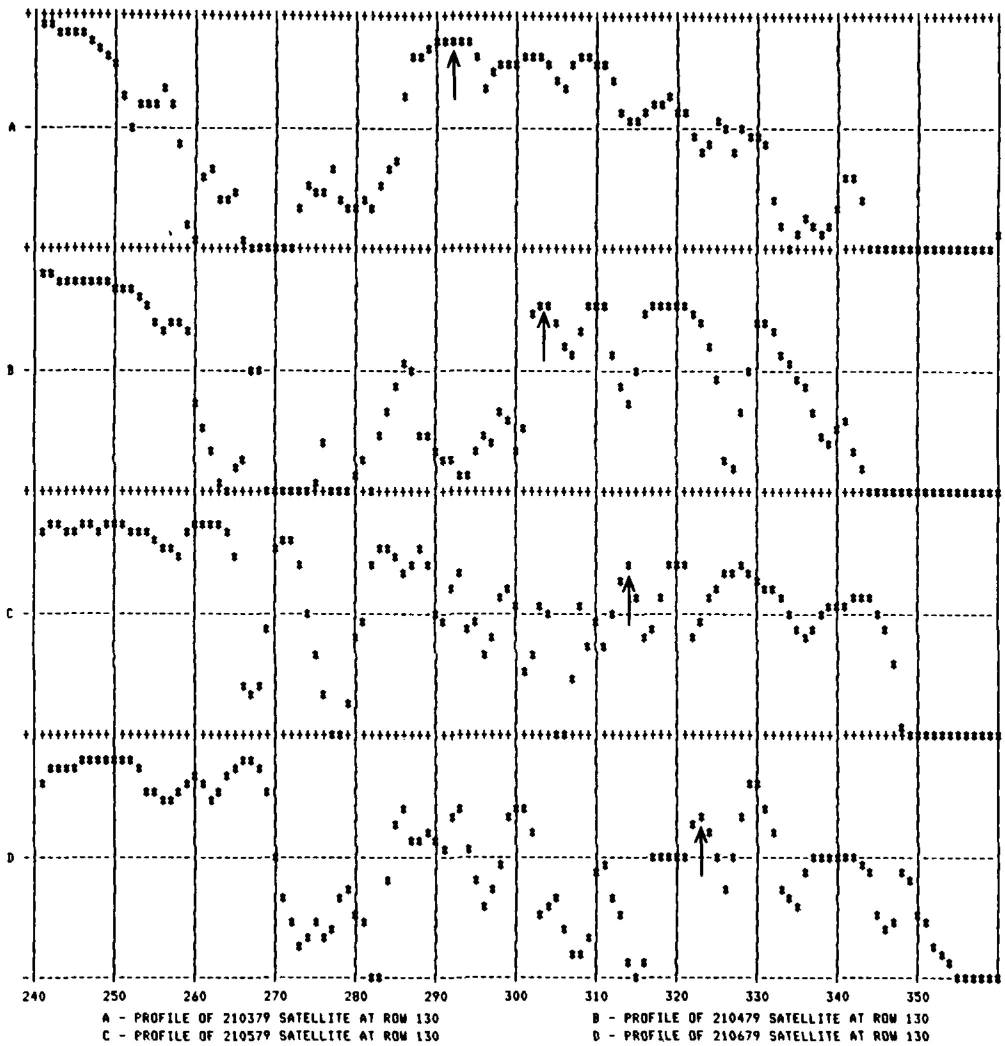

Figure 53. Profile of 21/03Z-21/06Z satellite data at 1 hour intervals.

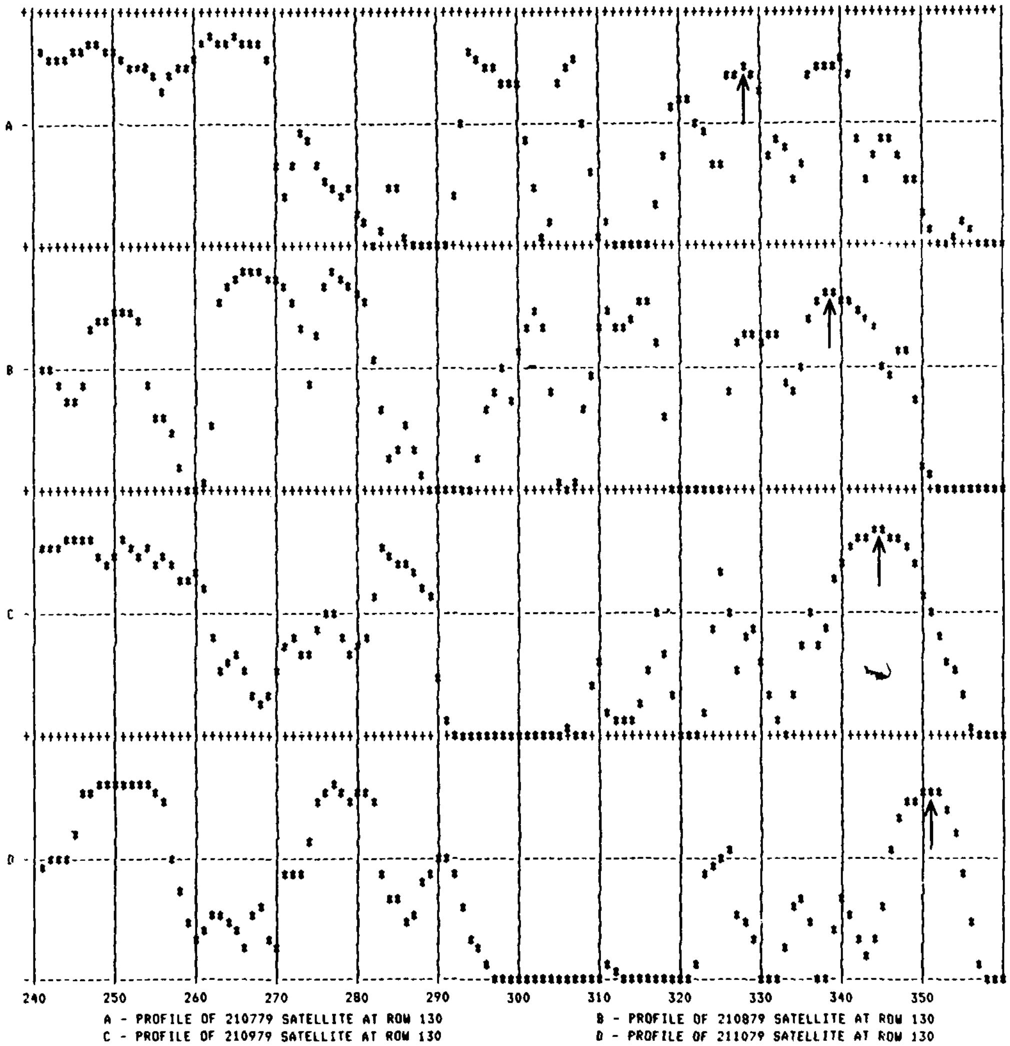

Figure 54. Profile of 21/07Z-21/10Z satellite data at 1 hour intervals.

trivial task and is made more difficult given the limited data coverage of the MOS grid network. In this case study the ESP showed little movement beyond the 06Z forecast, thus the ESP cloud field if moved at the speed of the satellite cloud field would simply be advected forward at the same rate that the satellite cloud field has been moving for the past few hours. This adjustment would be a linear extrapolation of the satellite cloud field movement. It would however be an improvement over the MOS forecast since the MOS moved the cloud fields too slowly (comparing the 12Z MOS forecast with the observed cloud fields).

A more sophisticated bogusing technique will be required to use both the extrapolated position of the satellite data, and the dynamics of model output, or an updated set of MOS type predictors using the satellite and/or synoptic observations that are available. A number of such techniques have been proposed that produce a short range forecast based on the extrapolation of semi-hourly GOES imagery, as well as short range models based solely on GOES satellite imagery (Muench, 1980, 1981).

4.0 SUMMARY

4.1 Results/Conclusions

The intent of this research was to assemble enough software to evaluate the proposed 'FOCAST' technique for using satellite data to monitor and adjust the movement of cloud fields derived from model output forecasts. This adjustment should improve general weather forecasts derived from the model guidance. Several flow diagrams were compiled to show how a forecaster could gather, display, and analyze satellite and model output data. Algorithms were then developed to use geostationary satellite data to monitor and adjust cloud fields estimated from model output statistics (MOS), and a case study was used to demonstrate and evaluate the method.

When applying the forecast adjustment method ones major assumption had to be made. Since model output data were only available at a limited set of data points interpolation was necessary between those points to produce a cloud 'field'. The method of interpolation will produce a cloud field that shows a gradient of cloud categories that may not be totally representative of atmospheric cloud fields.

The infrared satellite data were used without applying corrections for parallax error or atmospheric attenuation, and satellite cloud fields were not stratified by cloud type or height. It was assumed that the highest (coldest) cloud tops represent the highest cloud fields (and the highest ceilings).

A most difficult portion of the proposed shortrange forecast method is subjective intercomparison portion where the cloud fields must be matched, to make a comparison between the predicted and observed movement or growth. The forecaster must make a number of decisions when comparing the MOS and satellite cloud fields such as the type of cloud represented by the satellite, and the dynamics involved in the genesis of the MOS cloud field (the so-called Estimated Satellite Product, ESP). Of course we envisioned that the forecaster would use a new computer-interactive display system to perform the intercomparison.

With these assumptions and limitations of the data and method in mind, the techniques were evaluated to determine if the new forecast method is practical and would prove useful for short range forecasting. The data were successfully displayed with a common coordinate system used for both the satellite and MOS cloud fields. This in itself is a very useful forecast verification tool. The two techniques used to follow the movement of the ESP and satellite cloud fields also proved to be a valuable method for the analysis of the lateral movement and expansion or decay of the cloud fields.

When a cloud field is forecast by use of the MOS equations, and its movement can be followed and compared to a like field on the satellite image, the forecasting scheme can be used to monitor its position and verify the model output forecast. The dynamics that caused it to be in error, however, are not a part of the method. Thus the adjustment technique used for the cloud field should include the 'revised dynamics' of the cloud system. The forecast adjustment method can also be used when the MOS does not forecast a cloud field and one can be tracked on the satellite imagery. In this case the forecast can be amended to include the cloud field and its movement extrapolated from the satellite imagery.

4.2 Recommendations for Further Research

It became obvious through the course of this research that more data were required at each step in the production and evaluation of the ESP's and the application of the forecast scheme outlined at the outset of the study. The use of MOS type cloud predictors appears to be an acceptable method for producing cloud fields that represent model output elements, however, they should be expanded to include (1) a finer data coverage -- for example an LFM grid sized network, and (2) an increase in the number of MOS categories at higher cloud levels to facilitate matching of cloud fields with satellite data. If new satellite data or combinations of satellite and surface data could be used to estimate cloud thickness or base it would be a most valuable addition to the method. Another recommendation would be to use additional data, in particular satellite-derived explicit cloud fields and atmospheric sounding data, along with the current MOS predictors.

If the proposal outlined by Voner Haar et al., (1977) Buss (1981) was pursued with a larger combined data set (e.g., on the scale of the current MOS equation derivation) or at the least satellite data were archived and used as a predictor in a MOS short range forecast equation, satellite data could, in turn, be used to <u>update</u> that forecast at intermediate times. For example, at present, the MOS are not 'rerun' midway between normal times because a full set of predictor data is not available. If a set of predictors were based on GOES IR satellite data and satellite sounding information an update could be run at any hour into the forecast period when the satellite data were available.

Table 7 lists additional data that could be used in the forecast method proposed in this study.

Table 7

Proposed Data to be Used in the Short Range Forecast Method (Figure 1)

Observed Data	Model Output
Satellite	Model Output Statistics (MOS)
Synoptic Observations	LFM/PE Output Used to Generate ESP (Buss, 1981)
Radar	Regression of Model Output, Satellite, Radar, Synoptic OBS, Climatology
	Individual Model Output Elements
	Implied Cloud Fields (Jet Stream, Cyclone, Vorticity Center)

In addition to using MOS with a higher data resolution and increased height categories as stated earlier, a further attempt should be made to monitor individual model output elements such as moisture fields, and derived model fields such as vorticity and pressure center movement. Also larger scale feaures such as the distinct cloud bands along jet streams and cyclone and vorticity center cloud features could be tracked using ESP and actual satellite data along with the corresponding model forecast for the movement of those centers. An additional use for the forecast scheme would be to follow the progress of cloud fields that are not easily resolved by the models, such as mesoscale convective complexes (MCC's).

With the increased research in the area of mesoscale analysis and forecasting the integration of a single station's radar and satellite displays with a mesonetwork of observing sites could be used to develop a local climatology that could in turn be used in a MOS type forecast.

The observations from the station and its network could then be used, statistically, to monitor the progress and if necessary adjust the local forecast.

The key point for future research is that the output of the models and the observed satellite cloud fields must be 'bridged' both prior to, and following the progress of, the model output forecast. While improved interpretation of satellite data will aid progress toward this goal there is also a need for improved, and new, model output products. We suggest that a Quantiative Cloud Forecast (QCF) be added to the LFM class model output to strengthen the 'bridge' between the satellite and the model. Indeed, the Cloud Forecast Package at the AWS Global Weather Central is a beginning in this direction.

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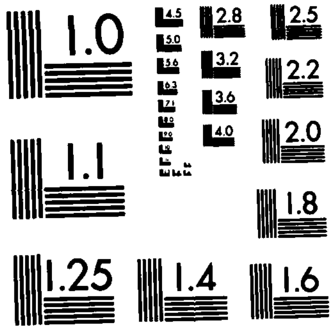

MICROCOPY RESOLUTION TEST CHART
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APPENDIX A

PORTIONS OF THE ORIGINAL RESEARCH PROPOSAL
PREPARED by Vonder Haar et al., (1977)

1. SUMMARY

The proposed research is directed toward improved forecasting of cloud conditions, precipitation and other aspects of aviation weather at the mesoscale during the 0-6 hour period. It uses quantitative satellite data from geosynchronous satellites as a key input to the forecast mix. In addition, the proposed research incorporates conventional forecast information (empirical, numerical or MOS-type) and real-time weather depictions from station data with the satellite data into a new methodology termed FO-CASTING.

Using satellite data sets provided by AFGL, augmented by additional data from the CSU Satellite Groundstation and conventional data, plus model output from the SKYWATER network, we will design and test the FO-CASTING technique over a variety of mesoscale weather conditions.

Some of the research effort in the early period of the contract will be directed toward improving the quantitative interpretation of the satellite data. Throughout the research period the meteorological objectives will be approached with the aid of the latest micro-computing innovations.

By combining the current technical and data base with the new ideas for focused nowcasting, prospects seem very good for favorable results; namely, improved shortrange aviation forecasts.

2. RESEARCH PLAN

In the early 1970's CSU scientists and AWS officer-students, together with AFGL (formerly AFCRL) scientists, pioneered the use of quantitative satellite data for short range forecasting. The results were favorable [see Sikula and Vonder Haar (1973), Enclosure 1] and showed definite skill even when the early visible-light-only ATS data were used. Conover (1974) improved the method even further.

The research proposed in this document is planned to improve, even further, the skill of objective shortrange forecasts of cloud conditions, precipitation and other aviation weather parameters by using the following new technology and methods not available in the early 70's:

a) the digital, high resolution visible radiance and infrared radiance measurements from the GOES; collected at research-quality ground-stations (see Enclosure 2)

b) the video-linked interactive computer systems that allow efficient use of the satellite data [McIDAS at AFGL; ADVISAR at CSU (see Enclosure 3 and the Report of the Interactive Video Workshop (1977), for examples of ADVISAR capability)]

c) the realtime availability of forecast products and weather depictions from NMC and GWC; including the new high resolution Model Output Statistics (MOS) methods.

2.1 The FO-CAST Method

We envision a new method of shortrange forecasting termed FO-CAST (Focused Nowcasting) in which both the digital satellite data and the real-time conventional products both play key parts. Essentially this method compares a forecast of cloud conditions, precipitation, etc. with a skill-full nowcast (eg. projection, extrapolation) using satellite data; and both in turn with an intermediate term weather depiction for verification. The method then allows the forecast team to focus on those areas where satellite nowcasts are providing new and better information than the conventional forecast methods. The FO-CAST method is outlined in Figure 1. It inherently optimizes use of both the satellite and the conventional forecasts for time and cost efficiency. In the notation of Figure 1 we first determine those regions in a sector (eg. the U.S., the midwest, etc.) where

$$A - B = C$$

namely, where the difference between the verification at an intermediate time and the NMC or MOS forecast seems to be explained by the satellite nowcast. Such areas are then prime candidates for another satellite nowcast using the latest data.

If $A - B = 0$, conventional methods verify and no special use of satellite data is needed. If $A - B > 0 \neq C$, then neither conventional nor satellite methods are working. This is information in itself!

Several key research questions are components of the proposed research on FO-CAST.

a) Does the satellite method of Sikula, Vonder Haar and Conover (the statistical method) show improved skill when used with the GOES data?

b) How does such a statistical approach compare with simple objective extrapolation of the cloud fields seen in the digital image sequence? Can certain "delta" parameters determined from the satellite sequence be extrapolated better ·an the basic scene?

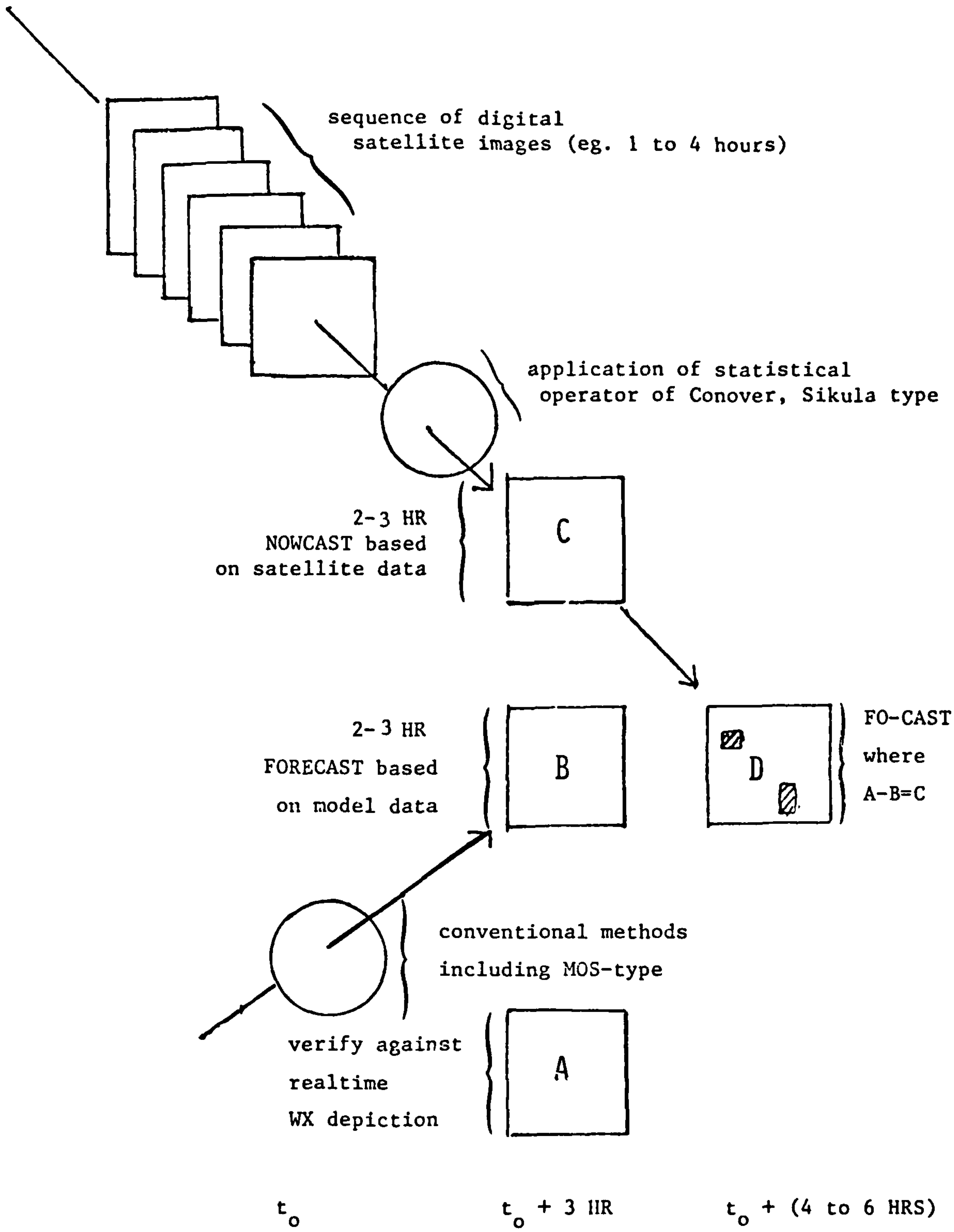

Figure 1. General Layout of the Focused Nowcasting (FO-CAST) method for shortrange forecasting aided by satellite data (see text for description).

c) Does the NMC or MOS type approach systematically score (or fail) in certain cloud situations? The same for $A - B = C$ cases?

d) What is the frequency of occurrence of $A - B \neq C$? Is it random or systematic? Why? [This leads into research (eg. on models) beyond the scope of the present proposal.]

Our research plan includes study of these items as well as refinement of the FO-CAST method in collaboration with AFGL scientists. We will direct our current capabilities in computer-based satellite and conventional data mixing toward the FO-CAST problem. Methods to manually intervene in the forecast will be developed. We will test the FO-CAST method on independent data and evaluate the relative accuracies of various methods.

APPENDIX B

LIST OF REPORTS
PUBLISHED UNDER THE PRESENT CONTRACT

1. Scientific Report No. 1

   Haass, U. L. and T. A. Brubaker, 1979: Estimation of Lateral and Rotational Cloud Displacement from Satellite Pictures. AFGL-TR-79-0287, 16 pp., October.

2. Scientific Report No. 2

   Haass, U. L., 1981: Cloud Tracking from Sateliite Pictures. AFGL-TR-81-0205, 148 pp., July.

3. Scientific Report No. 3

   Buss, N. E., 1981: A Quantiative Technique for Short Range Weather Forecasting Using Numerical Weather Prediction Guidance and Digital Satellite Imagery. AFGL-TR-81-0206, 63 pp., March.

4. Special Report

   Reinke, D. L., P. Laybe and T. H. Vonder haar, 1982: Compendium of Software Support for AFGL's Short Range Forecasting Project, Atmospheric Scheme Report, Colorado State University, 49 pp., March.

5. Final Report

   Reinke, D. L. and T. H. Vonder Haar, 1982: Weather Forecast Adjustment Using Model output Cloud Fields and Digital Satellite Data, AFGL-TR-82-0168, 110 pp., August

AFGL-TR-79-0287

ESTIMATION OF LATERAL AND ROTATIONAL CLOUD DISPLACEMENT FROM SATELLITE PICTURES

Uwe L. Haass
Thomas A. Brubaker

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Scientific Report No. 1

October 1979

Approved for public release; distribution unlimited

AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AFB, MASSACHUSETTS 01731

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFGL-TR-79-0287	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ESTIMATION OF LATERAL AND ROTATIONAL CLOUD DISPLACEMENT FROM SATELLITE PICTURES		5. TYPE OF REPORT & PERIOD COVERED Scientific Report, No. 1 6. PERFORMING ORG. REPORT NUMBER 1
7. AUTHOR(s) Uwe L. Haass and Thomas A. Brubaker		8. CONTRACT OR GRANT NUMBER(s) F19628-78-C-0207
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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES This work was supported by Army Research Office Grant DAA G29-76-G-0324 and AFGL F19628-78-C-0207
Presented at the Workshop on Computer-Analysis of Time-Varying Imagery Philadelphia, PA, April 5-6, 1979

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Mesocale forecasting
High resolution forecasting
Cloud rotation
Cloud displacement

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Weather forecasting in the mesoscale range often remains problematic due to the rapid changes. With the advance of high-resolution imaging techniques, satellite pictures taken in short time intervals can be employed to improve interpretation and prediction of atmospheric situations by analyzing cloud motion and size parameters. Knowledge of these parameters allows estimation of wind fields as well as the establishment of

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time series in order to model the cloud development and extrapolate from past observations.

Our objective is to find estimators that reveal not only information on lateral (x-y) displacement, but also on rotation of clouds. These estimators should perform well for a variety of meteorological conditions.

Currently, a variety of cloud displacement estimators are competing for computational convenience and versatility in application [1-6]. Our work concentrates on methods applying the Inner Product (popularly called cross-correlation) since we hope to combine a mathematically elegant theory with efficient strategies for application.

Particular emphasis will be directed to:
(1) Improvement of peak detection on the Inner Product surface by pre-filtering of the pictures. This method will be called Accentuated Correlation (AC). An analysis of the given signals and their properties in the spatial and frequency domain leads to the theoretical background of AC. AC will adopt ideas developed for the one-dimensional case [7] and incorporate a recently suggested exponential type of pre-filtering [8]. It can be shown that pre-filtering with a truncated inverse filter leads to better results than the exponential type.

(2) Employing Inner Product methods on the polar-coordinate contour functions of two clouds to determine their relative rotation.

At the time of the workshop, results of the suggested methods will be presented for the case of simple, single clouds. An extension for more complex cloud situations is currently under work.

AFGL-TR-81-0205

CLOUD TRACKING FROM SATELLITE PICTURES

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July 1981

Scientific Report No. 2

Approved for public release; distribution unlimited

AIR FORCE GEOPHYSICS LABORATORY
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ABSTRACT

CLOUD TRACKING FROM SATELLITE PICTURES

Satellite pictures taken in short time intervals are employed to estimate the lateral (x-y) and rotational displacement of clouds. Several methods of motion analysis are introduced based on different signal characterizations and various degrees of image abstraction. Using the discrete luminance information (half-tone picture), the maximum of the inner product surface of two consecutive images serves as a lateral displacement estimator. This dissertation demonstrates how the maximum peak detectability can be improved by prefiltering with a non-causal planar least-squares inverse filter. Although this filter is derived from theoretical considerations, the resulting high-pass frequency characteristic commends its use for another reason: since most of the cloud information, such as edges and texture, is embedded in the high-frequency parts of the image, the subsequent inner product operation takes only the homogeneous displacement of these features into account. For clouds that have undergone severe shape changes, a gradual shift to less restrictive frequency characteristics is suggested.

If the luminance values are fit to a vivariate normal surface, clouds or cloud fields can be traced by following the ellipses of equal density. This method retrieves lateral displacement, rotation and size changes.

Another technique makes use of a closed contour of the cloud. either the boundary or any contour of constant gray-level. This contour

is traced, re-sampled and transformed into a Fourier descriptor (FD) series. The resulting coefficients reveal direct information about lateral displacement, rotation and scale change. For sufficiently smooth contours, this information can be obtained from very few low-order coefficients. The inverse transform of the two lowest-order coefficients is an ellipse approximating the original contour in the least-squares sense.

Finally, the problem of parameter modelling and forecasting is approached by the introduction of a Kalman filter. Linear and non-linear models are discussed. The analysis of several cloud motion case studies, however, revealed a multitude of severely non-stationary effects that could not be accounted for. Further research is recommended.

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Spring, 1981

AFGL-TR-81-0206

A QUANTITATIVE TECHNIQUE FOR SHORT RANGE WEATHER FORECASTING USING NUMERICAL WEATHER PREDICTION GUIDANCE AND DIGITAL SATELLITE IMAGERY

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Scientific Report No. 3

March 1981

AIR FORCE GEOPHYSICS LABORATORY
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ABSTRACT

A technique was developed to monitor numerical weather prediction output with hourly digital satellite data. The technique is applicable to FOCASTING or Focused Nowcasting using a mix of nurerical forecast output, geostationary satellite data, and conventional observations. The process allows the forecast team to focus on areas of significant weather events, then integrate the current satellite observation with the 12 and 24 hour numerical guidance to produce a terminal forecast.

The numerical prediction information is used to produce an Estimated Satellite Product (ESP). The ESP is created by inputting the Limited Area Fine Mesh (LFM) observed and forecast data into a linear regression equation to produce a prediction equation for the existance of a cloud field that would be viewed by a satellite. The regression equations are developed by a stepwise procedure in which the predictand is the infrared radiative temperature observed by the GOES East Satellite. The predictors are made up of parameters that best represent the existence of a cloud, and are computed from LFM forecast data. Equations are developed for three tropospheric layers representing low, middle and high cloud regions. The regression equations developed are for a limited case of the early winter season.

The ESPs are developed for each hour of the forecast period by interpolation of LFM output. The ESP is displayed on the CSU ADVISAR in the same resolution and earth navigation system as the GOES imagery. This permits precise comparison between the LFM derived estimated satellite product and the actual GOES image for the same valid time. The

forecaster can isolate an active weather system by displaying a mesoscale window of the LFM grid network.

Several case studies are examined to demonstrate the feasibility of the ESP/Satellite mix in forecasting the onset and duration of ceiling height categories and precipitation.

COMPENDIUM OF SOFTWARE SUPPORT
FOR AFGL'S SHORT RANGE FORECASTING PROJECT

Funded by AFGL Contract No. F19626-78-C-0207

By

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March 1982

INTRODUCTION

The purpose of this compendium is to compile and document all software support necessary for the creation and evaluation of Estimated Satellite Products (ESP) based on Model Output Statistics (MOS), as described in AFGL Final Report, "Weather Forecast Adjustment Using Model Output Cloud Fields and Digital Satellite Data" (in press).

In the course of describing these methods the reader is introduced to a variety of current applications software available on the CSU man-interactive processing system. Additional details and questions related to the general COMTAL/ADVISAR system are noted in the references.

This paper is divided into four sections based on the flow diagram of Fig. 1:

I. MOS Data Processing and Display (ESP)

II. Satellite Data Processing and Display

III. Bridge Techniques (Comparison of ESP and Satellite Data)

IV. Compendium of Software (Program Listings)

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